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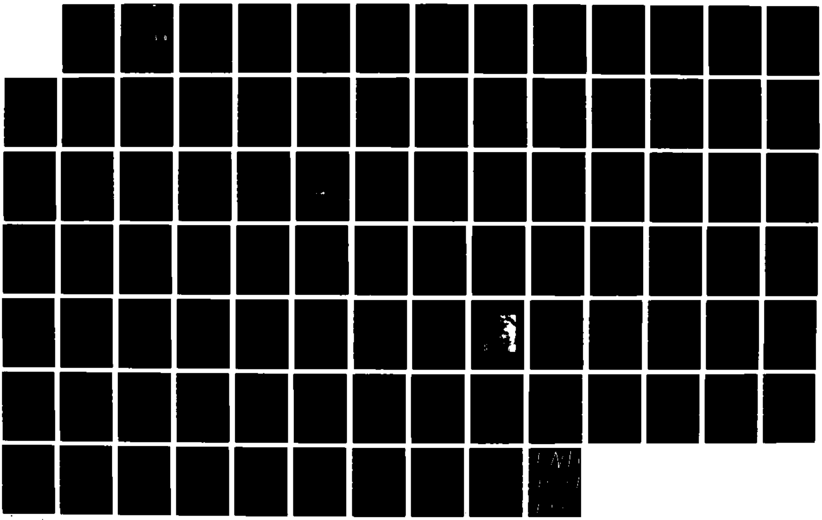

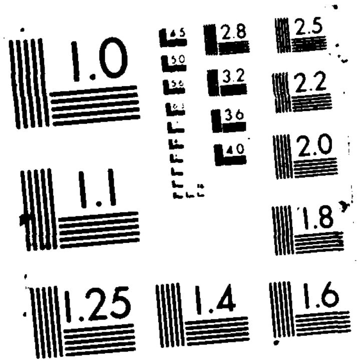
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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER AFIT/CI/NR 87- 119T	2. GOVT ACCESSION NO. AD A185 929
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) Thunderstorms With Snow: A Comprehensive, Empirical Study of Their Occurrence, Development And Structure	5. TYPE OF REPORT & PERIOD COVERED THESIS/DISSERTATION
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Harold Alan Elkins	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS AFIT STUDENT AT: Saint Louis University	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS AFIT/NR WPAFB OH 45433-6583	12. REPORT DATE 1987
	13. NUMBER OF PAGES 80
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)	15. SECURITY CLASS. (of this report) UNCLASSIFIED
	15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

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18. SUPPLEMENTARY NOTES

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THUNDERSTORMS WITH SNOW:

A COMPREHENSIVE, EMPIRICAL STUDY OF

THEIR OCCURRENCE, DEVELOPMENT AND STRUCTURE

Captain Harold Alan Elkins,USAF

1987

Thesis for the Degree of Master of Science (Research)

at Saint Louis University

80 pages

ABSTRACT

A comprehensive, empirical study is undertaken to outline the characteristics of thunderstorms with snow. Occurrences are documented over a 17 year period (1971-87) and related to the development of mid-latitude cyclones. Emphasis is placed on the role of cold air motion as an integral part of the cyclone life cycle. Data indicates a cyclonic and anticyclonic tendency of the air depending on the stage of development. It also suggests the occlusion may not contain warm sector air.

In order to understand the electrification process in a snowstorm the cloud physical microscale precipitation processes are analyzed. These are quantified and related back to the synoptic scale. From this,a conceptual model is created illustrating the structure of a thunderstorm with snow and is used to discuss the possible development.

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Professor Albert J. Pallmann

Professor Gandikota V. Rao

ACKNOWLEDGMENTS

This research would have never been completed as is without the help from some very important people. The author would like to acknowledge the contributions made by these individuals. First, Rich Molinaro helped with organizing the data and explaining the complexities of the computer systems. Bill Nichols and Pam Blakley spent long hours with the author discussing cyclone airflow analysis and its relationship to the development of thunderstorms with snow. Mr. Ron Przybylinski provided satellite data on short notice for one of the cases used in this study. Drs. J. T. Moore, A. J. Pallmann and G. V. Rao made many valuable suggestions during the writing of this thesis and receive the author's deepest appreciation. Finally but no means least, my wife Elizabeth who helped with the typing of the manuscripts and provided much needed support.

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1. Introduction

1.1 The Problems Associated with this Study

A thunderstorm with snow is a poorly understood meteorological phenomenon. Current literature (Kocin *et al*., 1985; Bosart and Sanders, 1985; Beckman, 1986) deals indirectly with thunderstorms with snow; very little has been documented on the occurrence and/or development of this phenomenon. The terminology is even unsettled. Snowburst, thundersnow, and mesoscale convective snowstorm have all been used to describe the same weather event. In this paper the convention established by Curran and Pearson (1971) will be used. Thunderstorms with snow will be referred to as TS.

TS present a significant forecast problem. Their accompanying heavy snows can paralyze any region especially urban ones. TS can have an impact across most of the nation. During the winter of 1986-87 cities from Salt Lake City to Baltimore reported TS. The importance of better understanding these occurrences is obvious. Unfortunately, there is a plethora of problems and biases which need to be attended to before any understanding can be furthered.

Observations present the most fundamental problem in two ways. First, there is some doubt whether the observer will report what he/she believes can't happen. In addition, oberving lightning and thunder in moderate to heavy snow can be difficult. Multiple scattering by snow dampens the brilliancy of the lightning as well as muffling the thunder. Daytime observing is even more difficult with less light contrast and more noise interference. Second, a lot depends on how the observation is encoded. There is a tendency to place lightning and thunder in the remarks section and not in the weather code. TS+ is more accurate than S+ with remarks;furthermore, if the remarks are not archived with the observation, historical reviews may not obtain a representative picture of the weather occurring at that time. As far as accuracy, thunderstorms with snow are usually associated with continuous precipitation,so TS+ is preferred over TSW+.

Our tools for understanding the atmosphere and its processes do not offer a better picture. These include the following:

1) rawinsonde winds represent only the horizontal component of the total wind vector,
2) thermodynamic diagrams represent lapse rates with respect to liquid water and exclude the

ice phase,

3) radar data is less effective in snow since the reflectivity of ice is about 25% of the reflectivity of liquid water,

4) most widely used satellite enhancement curves don't focus on the temperature range of -10° to -20° C giving biased signatures,

5) pressure data doesn't give a three dimensional picture and can't be used as a material surface,

6) overextension of geostrophic theory has led to biases in our analysis,interpretation,and understanding of atmospheric processes (e.g. instabilities,vertical motion production,etc),

7) current understanding of thunderstorms evolved from air mass and warm sector types and may not be complete.

1.2 Objectives

In light of the biases just described this study will stay close to observational evidence. An empirical approach will allow a comprehensive treatment with as few assumptions as possible. With this in mind the main objectives of this research are:

1) to document the synoptic-climatology of the occurrences of TS,

2) to examine the development of TS bearing

cyclones,

3) and relate the growth of the cyclones circulation to the cloud physical microscale precipitation and electrification processes.

2. Literature Background

2.1 Thunderstorms with Snow

As alluded to earlier very little can be found in contemporary literature dealing directly with TS. Curran and Pearson (1971) made the first attempt at explaining TS. They scanned surface observations from February 1968 to April 1971 and found 76 reports of TS. In order to draw accurate conclusions from the upper air data, they further refined the rawinsonde stations to within 3 hours and 90 nautical miles of the surface reports. The 13 remaining stations were used to create a composite sounding which showed significantly high stabilities. They concluded convection had already begun at the time of sonde release, and no buoyant instability was present. Beckman (1986) presents TS from a satellite perspective. He discusses high instabilities are present as thunderstorms form in the warm sector and push into the cold air. He states that thunder may continue to be heard well after the mechanism producing it has dissipated. Beckman points to cold cloud tops as being an indicator of thunderstorms which is a questionable practice. The cirrus associated with jet streaks and extratropical cyclones often display cold cloud tops which is not related to thunderstorms. He does suggest

however that TS may not be that rare of an occurrence; data from this study supports this idea.

There is a larger volume of literature dealing indirectly with TS and contributing to the overall understanding of atmospheric processes. Kocin et al. (1985) critique a mesoscale model using a TS case. Unfortunately, two important rawinsonde stations were not available leaving their results questionable. Kocin and Uccellini (1985) document 18 East Coast snowstorms, several of which contained TS. Bosart and Sanders (1985),Emanuel (1985),and Sanders (1986) take TS cases and analyze for frontogenetical forcing and conditional symmetric instability. Their investigations are geostrophically based using pressure data which limits their interpretations due to the assumptions involved.

2.2 Cold Airflow in Cyclones

A significant portion of this study is devoted to cold air motions and their contributions to cyclone development. Information in this area was found to be lacking as well. Carlson (1980) contributes a great deal to this and to the methodology. He documents a significant role played by the cold air north of the warm front in cyclone development. Browning and Hill (1985) analyze the cyclonic tendencies of cold air

associated with polar vortices. Though they dismiss any similarity to Carlson's concept, they do provide insight into the mechanisms that produce the mature mid-latitude cyclone. Kocin and Uccellini (1985) demonstrate there is still a great deal of confusion regarding the structure and development of a mature mid-latitude cyclone. They extend Carlson's ideas to a mature cyclone,but their illustrations do not keep warm and cold sector flows seperate as emphasized by Carlson (1980).

2.3 Snow Production and Cloud Electrification

Byers (1965) and Mason (1971) provided the fundamental background in cloud physics. Jiusto and Weickmann (1973) relate ice crystal and snowflake structure to the processes that created them. Heymsfield (1977) provides detail about these processes from his aircraft investigations of ice clouds. With the aid of Takahashi (1978) these can be linked to the electrical development of TS. He emphasizes the thermoelectric effects in ice as the primary generation mechanism of electrical charge in winter convection.

3. Methodology

3.1 Data

Four cases were selected for extensive investigation; other cases were analyzed as they occurred during the winter of 1986-87. The first two cases cover both Missouri and Illinois on 25 February 1979 and 14 April 1980. The third case was chosen for its open wave development over Georgia and and the Carolinas on 24 March 1983. Finally, during 26-27 March 1983 Eastern Nebraska experienced heavy snow from both the open wave and mature phases of the cyclone. A control case (no thunder) was to be used from the winter of 1986-87 for comparison,but the storms either contained TS or there were problems with the data.

Surface data was available for every hour and usually plotted every 3 hours. Upper air data was available every 12 hours. Isobaric and isentropic surfaces were analyzed at many levels. Pressure data were converted to isentropic using the Duquet (1964) isentropic program. Soundings were interpolated vertically to potential temperature levels from the surface, every 2°K, to the 350K level and every 10°K thereafter. Interpolation is linear for all parameters. The Montgomery streamfunction ($\psi = C_p T + gz$) was computed through a vertical integration of the hydrostatic

equation in isentropic coordinates upward from the ground.

3.2 Airflow Analysis

This is similar to the conveyor belt analysis of Carlson (1980) and Browning and Hill (1985) in their conceptual models of cyclones. Cyclogenesis is analyzed by using the cyclone's three dimensional airflows with respect to a thermal field.

3.3 Objective Analysis

Objectively analyzed fields of u,v,q,ψ,and p were obtained using a Barnes (1973) scheme. The data were placed on a 23 (x axis) by 15 (y axis) grid (southeast case) and a 20 (x axis) by 19 (y axis) grid (great plains case) with 127 km spacing on a polar stereographic map projection true at 60°N. Figure 1 shows the response function obtained from the objective analysis scheme. Just under 40% of the 2Δ wavelength's amplitude is resolved.

3.4 Relative-Wind Isentropic Streamline Analysis

In this scheme the estimated speed of the system is subtracted from the u and v wind field. The analyzed streamlines can then be used as approximate trajectories. In order to account for saturated environments, equivalent potential temperature (theta-e)

pressures are substituted for the isentropic pressures. This was applied by Carlson (1980). It is recognized that other processes such as radiative heating and cooling play a role in the atmosphere, but no attempt will be made to encorporate these at this time.

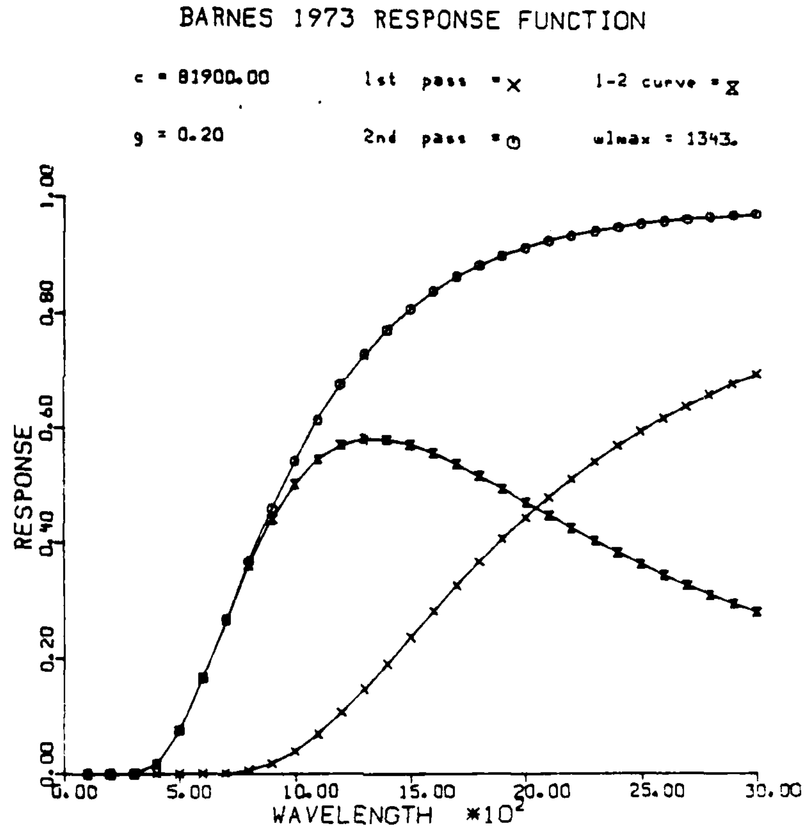


Fig. 1 Barnes (1973) response function.

4. Documentation of Thunder in Snow Events

My own experience with four systems that produced TS wasn't enough to establish any type of trend. The Daily Weather Map (NOAA, 1971-1986) series offered a quick, convenient means of tracing the occurrences of TS over an extended period. Curran and Pearson (1971) ended with 1971 so that was a logical starting place. Of course the Daily Weather Map series contains only the 1200 GMT surface and 500 mb charts,but the previous 6 hour weather code allows 25% of each day to be covered with the one chart. The 16 year period (1971-1986) helps make up for the shortcomings of the data source. This method only gives one or two reports of TS per storm where Curran and Pearson (1971) surveyed all observations. This investigation wasn't intended to be complete but to outline the significant areas of development. Reports from the winter of 1986-87 spanned all hours and were recorded as they occurred. In total, 43 cases were documented; nine of the cases were recorded during 1986-87.

The occurrences were plotted with respect to a mature mid-latitude cyclone (Fig. 2). This composite model represents the open wave and mature phases of the cyclone. In the initial search a closed 500 mb

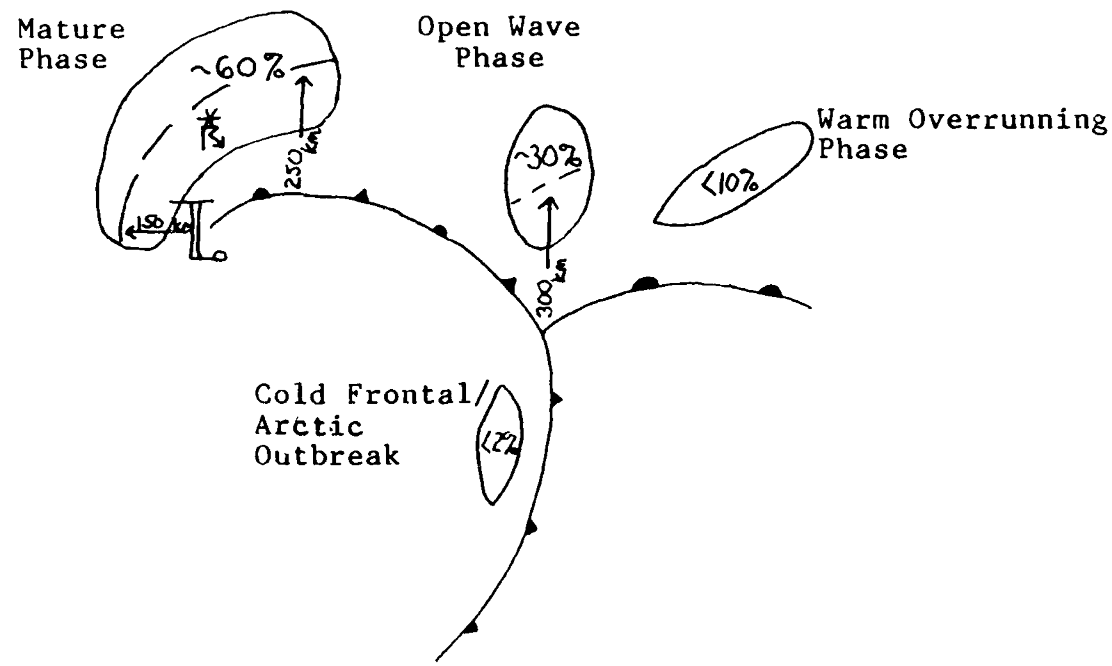


Fig. 2 Percentage of 43 TS cases recorded from Jan.1971 through Mar. 1987. Composite cyclone model combines the developing (open wave) and mature phases of a mid-latitude cyclone.

height contour dictated that the occurrence was associated with a mature cyclone while others were labeled open wave. Later, these will be related to the airflows that comprise a cyclone. Since they are not related to the cyclone, reports from lake effect snow squalls are not included in this portion of the study.

The most significant area of TS development is in the northwest quadrant of the mature cyclone. Approximately 60% of the cases documented in this study are located here. Snowfall totals range from a few inches to around 3 feet. The average distance from the surface low is 250 km to the north decreasing to 150 km to the west. The open wave phase of the developing cyclone constitutes the second greatest area of occurrence. Approximately 30% of the cases are located here. The average distance is slightly greater than the mature phase and is 300 km north of the developing surface low. Total accumulations are generally a foot or less since the speed of the system is much greater at this stage of development. The third area is classified as warm overrunning development. Less than 10% of all occurrences are located here; no spatial variation was attempted. Beckman's ideas would most likely fit into this area. The last area is the poorest documented with only one system showing this

tendency. A squall line of TS formed along a strong cold front in the Great Basin. TS reports were behind the frontal passage. This area also represents the suspected occurrences associated with arctic outbreaks. The conditions necessary for this development will be elaborated on later in the paper.

Beckman (1986) suggests a possible seasonal and diurnal trend. Table 1 gives occurrnces by month and shows a gradual peak around February. Cases revealed a preference for moderate cyclone development though this doesn't seem to be a prerequisite. A diurnal trend may be due to the ease of observing TS at night. Most cases used here are from 0600 1200 GMT due to the data source;however, the reports from the winter of 1986-87 spanned all hours of the daylight. The diurnal trend is questionable,and it is hypothesized TS occurrence is more likely related to the development of the cyclone. This will be shown in the next section.

Table 1
Monthly TS Variation

NOV	DEC	JAN	FEB	MAR	APR
14%	16%	19%	30%	16%	5%

TS location within the U.S. can be generalized to some degree although reports span from the Rocky

Mountains to the East Coast. Three main areas were noted from the cases in this study. They are: along the lee of the Rockies centered on Kansas, the Mississippi Valley centered on Iowa,and the lee of the Appalachians/East Coast centered on Maryland. Curran and Pearson (1971) give a preference for TS development in the central U.S.;no preference is given here.

5. Cyclone Development

5.1 Airflow Analysis

It is obvious from Fig. 2 that the emphasis should be placed on the cold air north of the cyclone. The mature and open wave phases constitute 90% of TS occurrences,but their relationship to cyclone development isn't clear. Surprisingly very little has been written about this cold sector of the cyclone.

As an example Fig. 3 is taken from Palmen and Newton (1969) which is often referenced (Holton, 1979) in the literature concerning cyclones and cyclone development. The descending cold air behind the cold front and the ascending warm sector air are well illustrated. Yet, the cold sector north of the warm front isn't given a part in the cyclone circulation at the open wave phase. The same is true for the mature phase (not shown) where the cold sector doesn't seem to have a significant role. This is in keeping with the idealized cyclone model from J. Bjerknes and Solberg (1922). The occlusion process (maturation) is explained as the cold front moving faster than the warm front and lifting the warm sector off the ground; an idea that has survived 6 decades of synoptic analysis. Most occlusion studies (Elliot, 1958; Kreitzburg and Brown, 1970; Wang and Hobbs, 1983) deal only

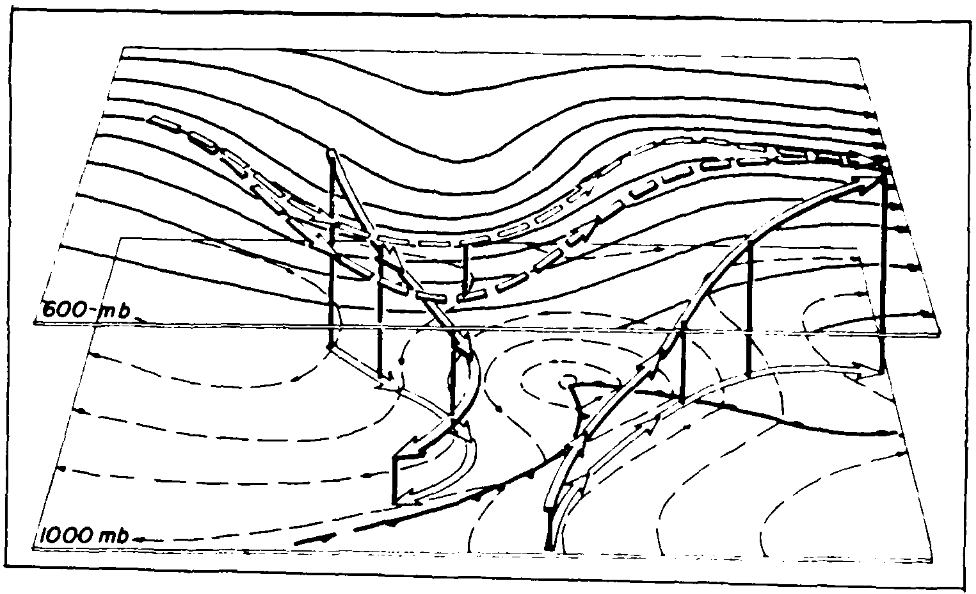


Fig. 3 Three dimensional representation of the airflow in a developing mid-latitude cyclone (Palmen and Newton, 1969).

with the structure of the occluded front (within 200 km of the triple point) and not the evolution. No literature was found concerning the northwest quadrant of the mature cyclone.

Later studies by Danielsen and Bleck (1967) and Carlson (1980) place more emphasis on the role of the cold sector. Figure 4 is taken from Carlson (1980) which summarizes these ideas. Carlson labels the cold sector as the cold conveyor belt (CCB). This is analogous to the terminology used by Green et al. (1966) to explain the warm sector or warm conveyor belt (WCB). Carlson states significant vertical motions are incurred as the CCB moves west toward the apex of the wave and out from under the WCB. The flow is anticyclonic as it ascends into the middle troposphere. The CCB and WCB merge along with the dry air associated with the jet to form the northern boundary of the comma cloud. This provides the well defined boundary seen on moisture channel satellite imagery. Carlson also emphasizes that at low sun angles visual imagery reveals a stair-step structure. This indicates the different levels of the CCB and WCB.

Browning and Hill (1985) take a similar approach in dealing with the cyclonic tendency of the cold sector airflow (Fig. 5). Their emphasis is with satellite

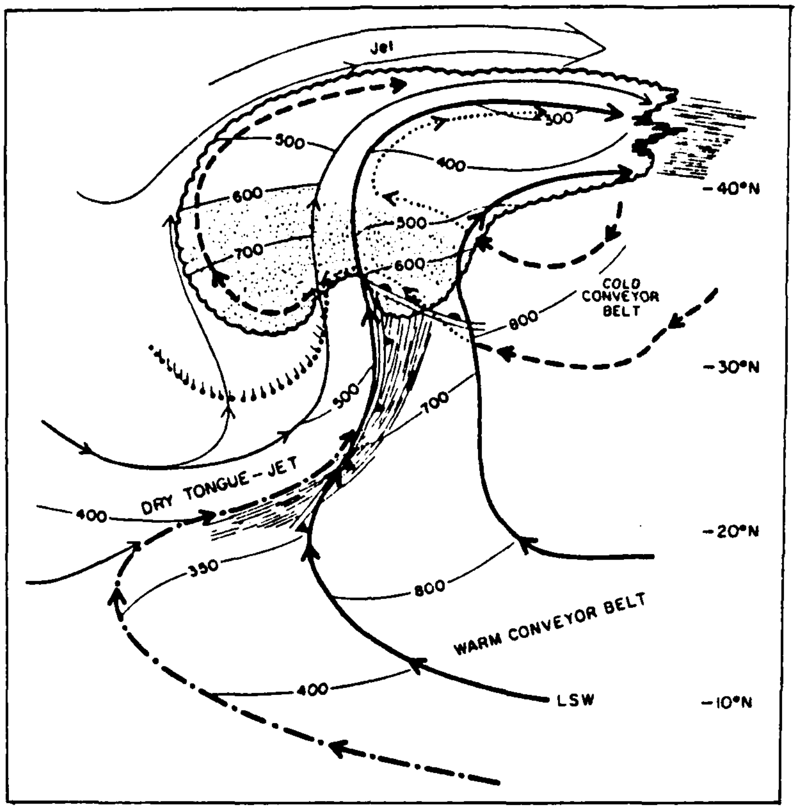


Fig. 4 Cold sector airflow (cold conveyor belt) in the open wave phase showing the anti-cyclonic tendency (Carlson, 1980).

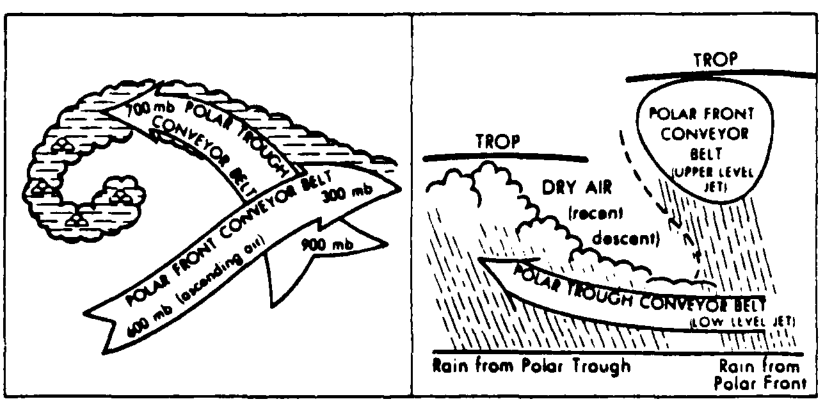


Fig. 5 Cold sector airflow (polar trough) in the mature phase showing the cyclonic tendency (Browning and Hill, 1985).

imagery,and the terms become confusing. They show the interaction of a polar trough with a polar front which is similar to the pseudo and instant occlusion but shouldn't be confused with the classical occlusion. Browning and Hill (1985) go on to compare their polar trough idea with that of Carlson's CCB but dismiss any similarity on the basis of moisture content. Two oversights can account for this difference: season and source. Their system was an autumn, oceanic one while Carlson used a winter, continental system which would be colder and drier. Most obvious of the differences is one is anticyclonic and the other is cyclonic. Since Carlson remained vague about the phase of the cyclone, Kocin and Uccellini (1985) extended his ideas (Fig. 6). In order to account for the classical occlusion they draw the WCB northwest of the surface low but above the CCB. Carlson is quite explicit about the separation of the CCB and the WCB. It is obvious at this point that a better picture of cyclone development must be constructed before any conclusions can be made concerning the connection with TS occurrences. The concept of airflow analysis during cyclogenesis helped bridge this gap. This simple approach allows the basic cyclone airflows to be viewed against a representative temperature field so to deduce the cyclone's development.

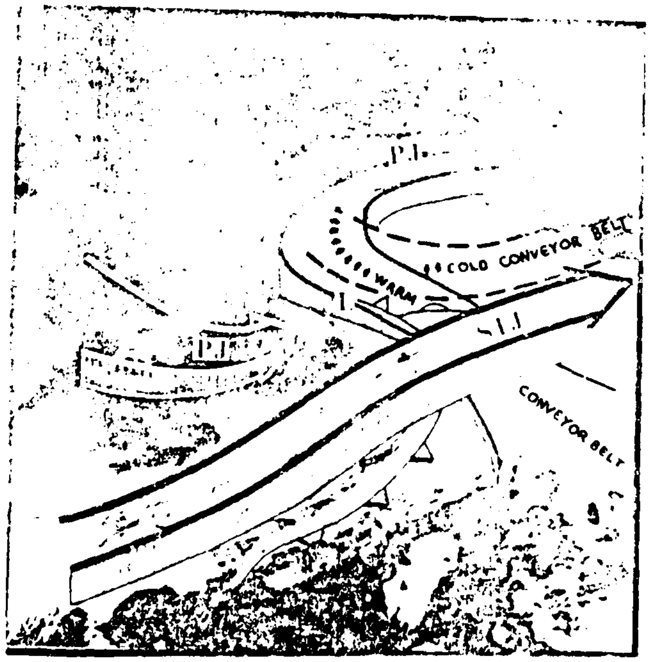


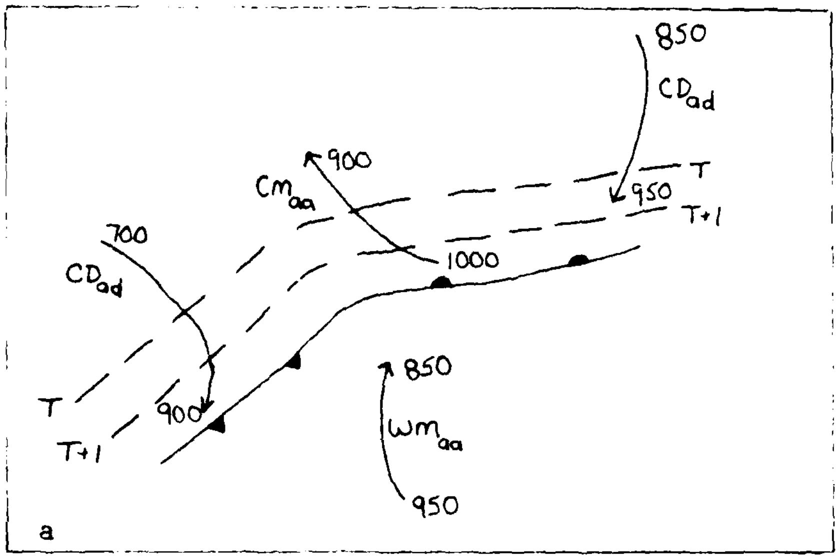
Fig. 6 Compromise between the classical occlusion and the conveyor belt analysis (Kocin and Uccellini, 1985)

In order to keep track of the different types of of airflows within the cyclone, they are labeled according to their source (warm/cold), water content (moist/dry), tendency (cyclonic/anticyclonic), and vertical motion (ascending/descending/horizontal). Table 2 summarizes the nomenclature for the airflows in the following text. In the figures to follow the main axis of the airflow is given, and it represents large volumes of air in motion.

Table 2
Cyclone Airflows

Type	Description
CM_{aa}	Cold Moist anticyclonic ascending
WM_{aa}	Warm Moist anticyclonic ascending
CD_{ad}	Cold Dry anticyclonic descending
CM_{ca}	Cold Moist cyclonic ascending
CD_{h}	Cold Dry horizontal
CD_{cd}	Cold Dry cyclonic descending
CD_{ca}	Cold Dry cyclonic ascending

Figure 7a shows the initial stage of development of a wave cyclone. Contemporary ideas on cyclogenesis, consistent with data used in this study, stress the importance of subsidence generated in the upstream ridge by confluent deformation. The subsidence (CD_{ad}) iniates cold air advection behind the developing cold front. The atmosphere as a continuum (Eringen, 1967) responds to this forcing and generates ascending air. The ascending air is fed by



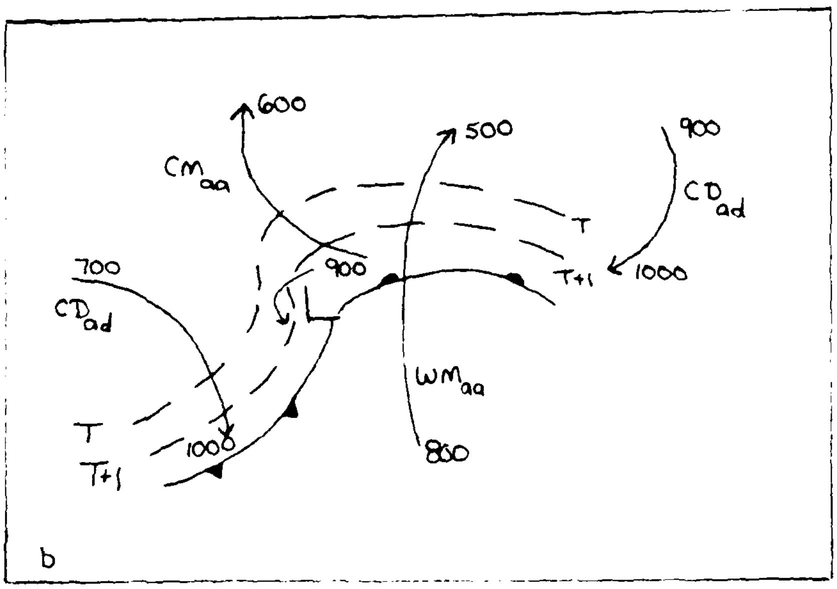


Fig. 7 Airflow analysis of a developing cyclone. Arrows represent the main axis of the flows labeled according to Table 3. Numbers represent pressure values to indicate vertical motion. Dashed lines are isotherms to show relative advection. a) Initial b) Open Wave c) Mature Cyclone.

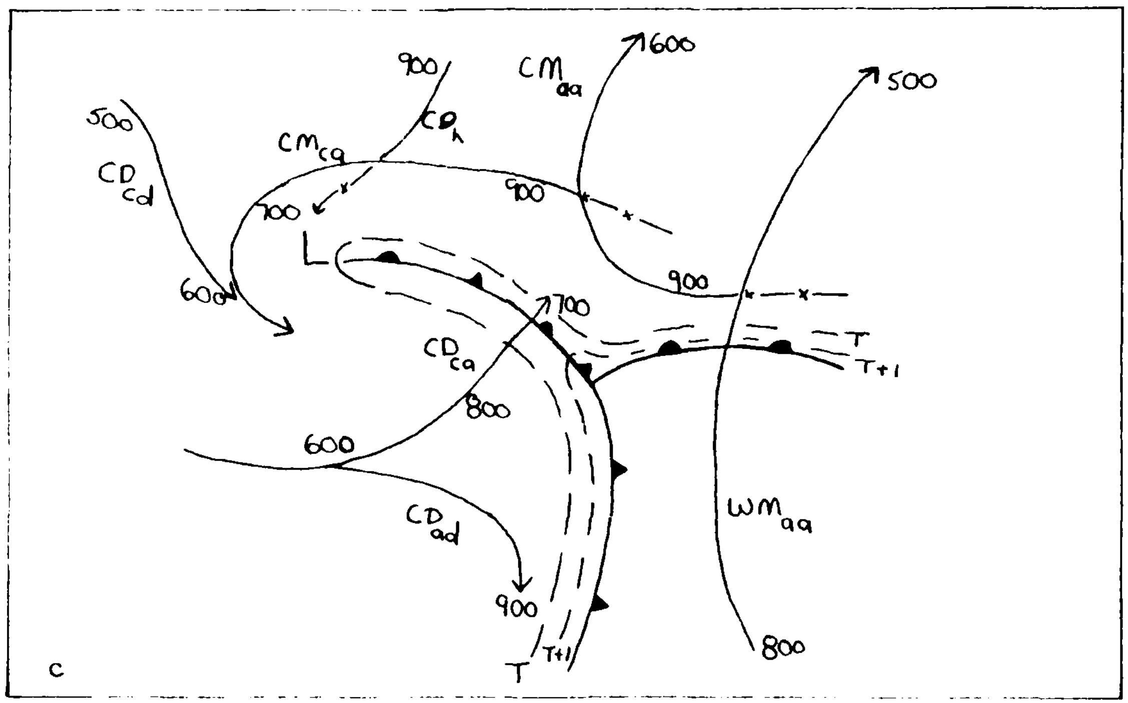


Fig. 7 Continued.

the warm (WM_{aa}) and cold (CM_{aa}) sectors. A thermal quadrapole is established across the wave. The strongest warm air advection (WAA) is associated with the CM_{aa} flow as it nears the apex of the wave and ascends. Curiously, the cyclone emerges from totally anticyclonic flow.

The open wave phase of the developing cyclone is given in Fig. 7b. The WAA at the apex has dramatically distorted the thermal field; the greatest pressure falls at the surface would be located under this area of strong WAA and vertical motion. Often at this stage an inverted trough can be analyzed northwest from the cyclone center (Saucier, 1955). As velocities increase, friction creates a small cyclonic flow at lowest levels. This is similar to the model presented by Danielsen and Bleck (1967).

As the system continues to grow, a thermal ridge becomes pronounced along what would be analyzed as the occluded front (Fig. 7c). The lowest pressure is found at the crest of this thermal ridge. It should be noted the distortion of the thermal field was produced by the cold sector airflows <u>not</u> the warm sector. These cold airflows are the cyclonic and anticyclonic components of a mature midlatitude cyclone. The different tendencies may be explained by the following conjecture. The CM_{aa} flow

moves from a strong temperature gradient and ascends to an increasingly weaker one. The pressure gradient force would weaken and a Coriolis deflection to the right would be realized. A sounding shows decreasing wind with height in this region. Conversely for the CM_{ca} flow, an increasing pressure gradient force is encountered and is accelerated to the left. From this viewpoint the pseudo,instant,and classical occlusion would be produced in the same manner; the perspective from satellite imagery would make them look different.

This conceptual model incorporates other characteristics observed in mid-latitude cyclones. The classical occlusion is formed by the intersecting of the CM_{aa},CM_{ca},and the CD_{ca} airflows. Depending on the amount of contrast between these flows there may not be a classical signature at all (Elliot, 1958). The northwest quadrant is comprised of three flows,CM_{ca},CD_{h} and CD_{cd}. As the CM_{ca} flow ascends it is replaced at the surface by the CD_{h} flow. Clouds are slowly entrained from top to bottom by the CD_{cd} flow. The low cloud reaches and dissipates at the jet axis (Nichols, 1987).

The primary importance of this technique and the conceptual model it produced is it shows TS development wholly in the cold air. Figure 8 shows

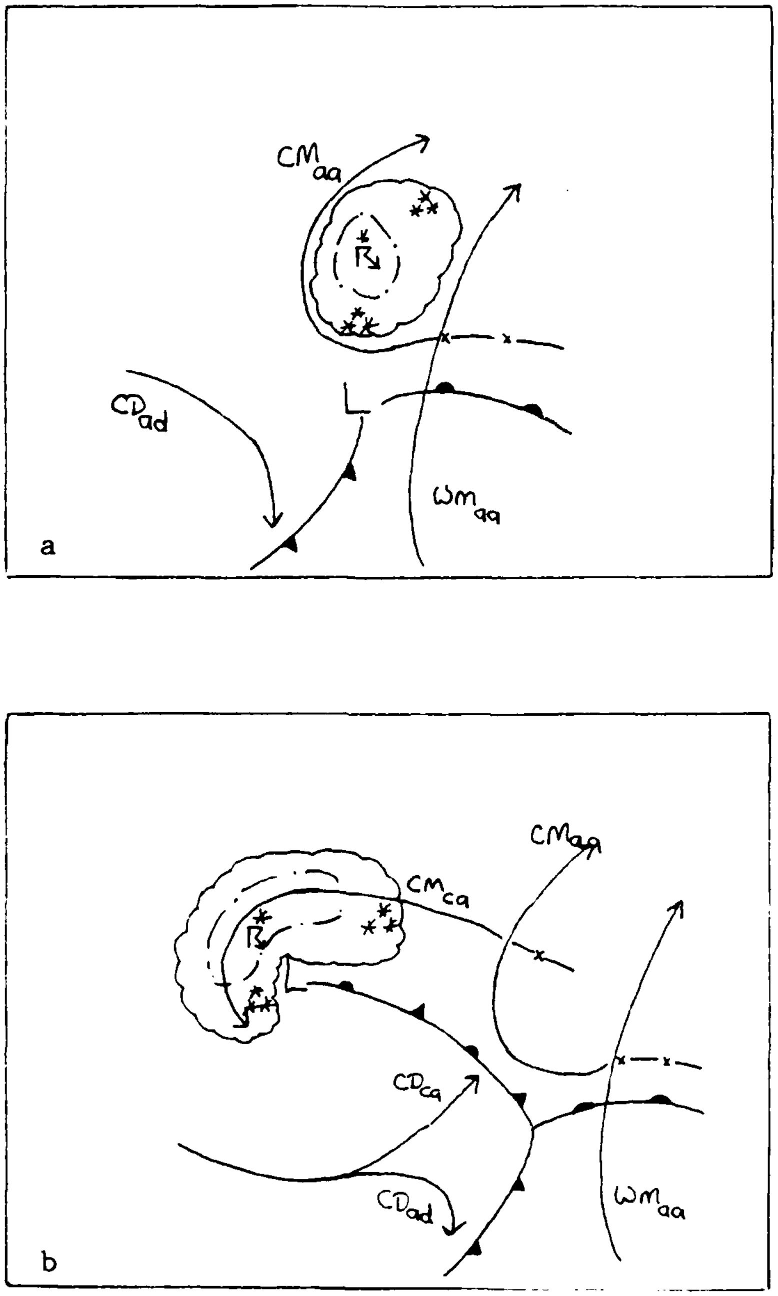


Fig. 8 TS occurence for the a) Open Wave and b) Mature phases with respect to the airflow analysis. Scalloped areas indicate moderate/heavy snow without thunder.

the open wave and mature occurrences of TS with respect to the airflow analysis. This reinforces the hypothesis that TS are closely related to cyclone growth. By removing the warm sector as a major consideration, it helps explain the lack of instability which perplexed Curran and Pearson (1971). This warm sector bias has clouded our interpretation of both cyclone and convective processes for many years. At this point it is interesting to consider the location of moderate/heavy snow without thunder and how it relates to the cyclone model as well. Studies such as Browne and Younkin (1970) only relate heavy snow to some upper level pressure feature which can be highly variable. Kocin and Uccellini (1985) compiled 18 different snowstorms with surface and upper air data. Most didn't report TS and were used to create a composite of moderate/heavy snow with respect to the cyclone model. This is shown in Fig. 8 as the scalloped areas. The areas of TS are contained within the heaviest snow suggesting the mechanisms producing both may be the same only to varying degrees.

5.2 Case Study Data

This section will highlight the case study data in order to document the ideas discussed so far. Some of the most dramatic cases of TS occur along the East Coast. Regretfully these types of storms present two

problems: orographic effects and lack of data due to the proximity of the Atlantic Ocean. With this in mind, cases over the Central U.S. are emphasized so only the basic mechanisms are analyzed. Four cases were selected for extensive investigation,and others were analyzed as they occurred. Unfortunately, unforeseen data problems in two of the cases prevented a complete analysis,but they still offer solid background information.

5.2a Southeast Missouri-Southern Illinois
25 February 1979

This case represents a surprise if there ever was one. Heavy rain changed to heavy snow accompanied by thunder across Southeast Missouri and Southern Illinois on the morning of 25 February. The heaviest snow fell on Cape Girardeau,MO with 24 inches of snow in about 12 hours. Interstate 55 was closed for 2 days. Salem,IL. was unable to release their sonde due to the snow problems.

Figure 9 contains the surface data for 0000 and 1200 GMT on 25 February (date/time represented as 25/00,etc. for the remainder of the paper). At 25/00 GMT the area of low pressure was beginning to develop over Central Mississippi. Moderate snow was falling over Southeast Oklahoma west of an inverted

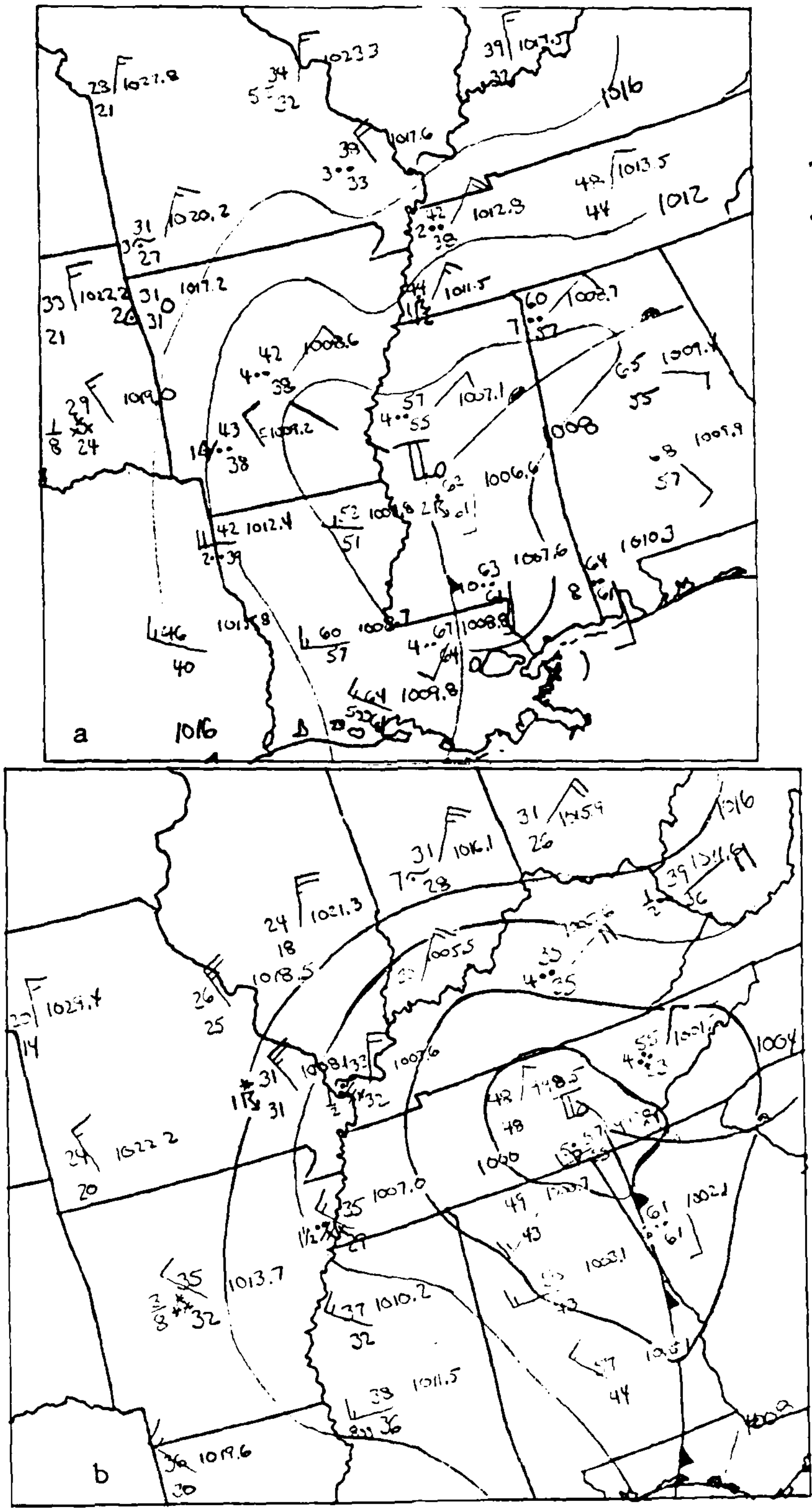


Fig. 9 Surface analysis for a) 25/00 GMT and b) 25/12 GMT. Standard station model plot. Solid lines are pressure analysis in mb.

pressure trough. By 25/12 GMT TS was reported at Cape Girardeau some 300 km from the lowest pressure in Central Tennessee. Though the Salem sounding data isn't available, this is recognized as a mature cyclone occurrence associated with the CM_{ca} flow.

5.2b St. Louis,MO. 14 April 1980

This case is the latest of the season documented in this study. East Central Missouri received about 6 inches of snow in about 6 hours. Figure 10 contains the surface analyses for 14/00 and 14/07 GMT. At 14/00 GMT the area of low pressure was developing over Western Alabama. A weak inverted pressure trough extended into Western Tennessee with a mixture of rain,ice pellets,and snow in Arkansas. By 14/07 GMT St. Louis was reporting thunder with moderate snow;the lowest pressure was around 250 km to the southeast.

Figure 11 contains the 298K isentropic surface for 14/00 GMT. Longview is missing and Oklahoma City's winds are missing. This surface intersects both the 850 and 700 mb surfaces giving a three dimensional view of this storm. The CM_{aa} flow extends from Tennessee to Arkansas and strong WAA is associated with this flow. The contrast of the CM_{aa} flow can be seen on the Monett sounding (Fig. 12) for

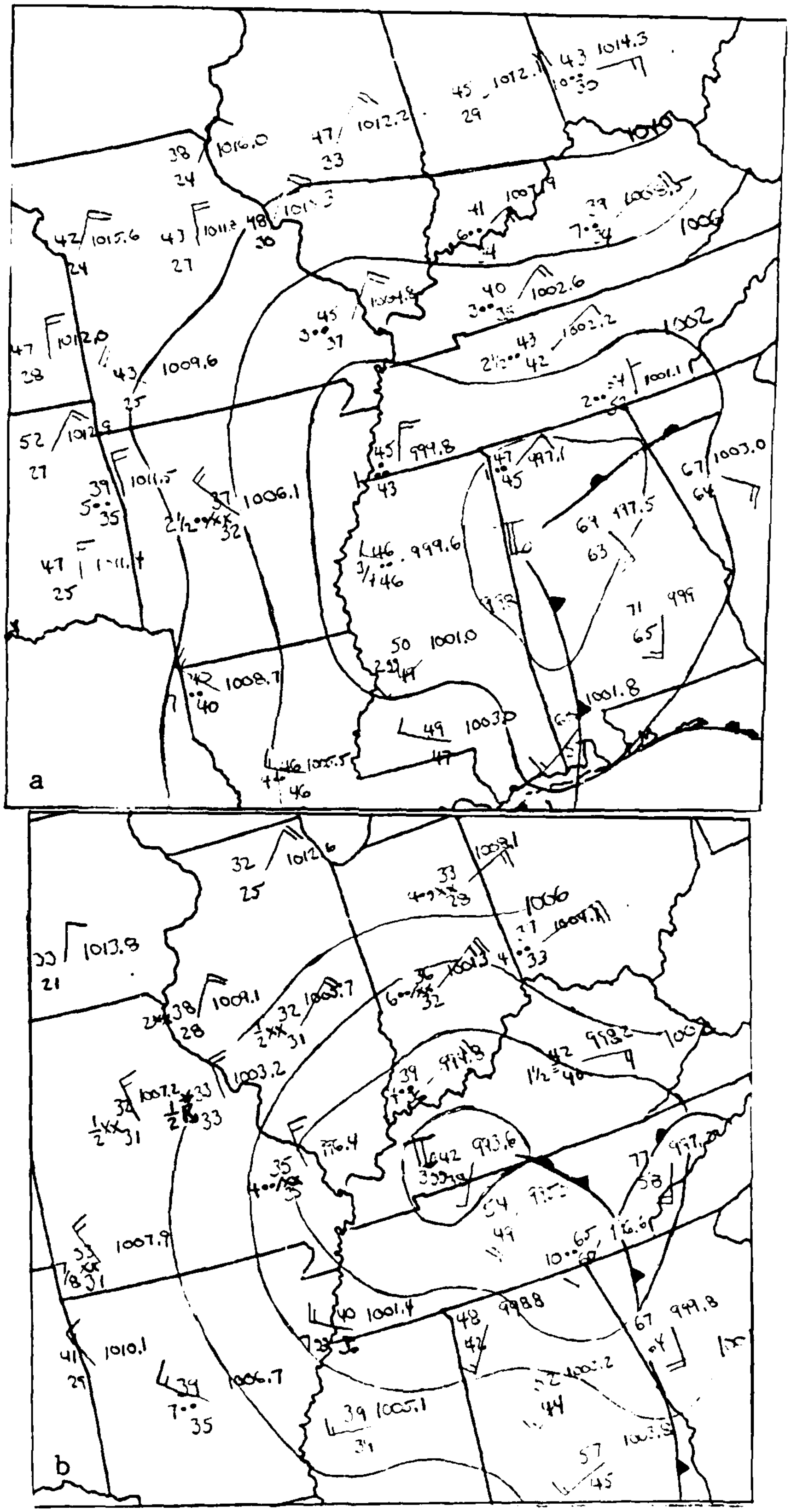


Fig. 10 Same as Fig. 9 except a) 14/00 GMT and b) 14/07 GMT.

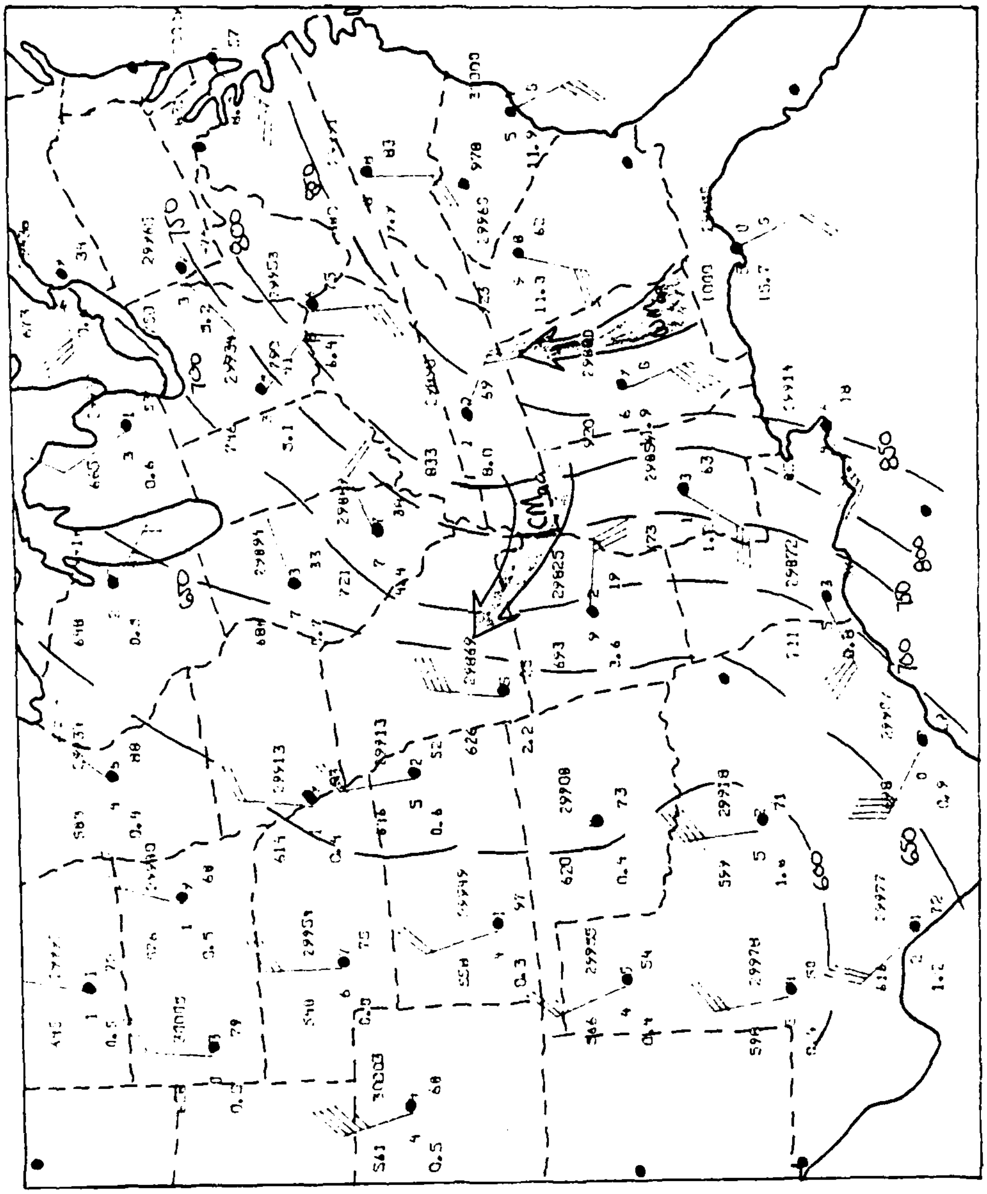


Fig. 11 298K isentropic surface for 14/00 GMT. Standard isentropic plot model. Dashed lines are isobars at 50 mb intervals. Broad arrows highlight the axis of the airflow.

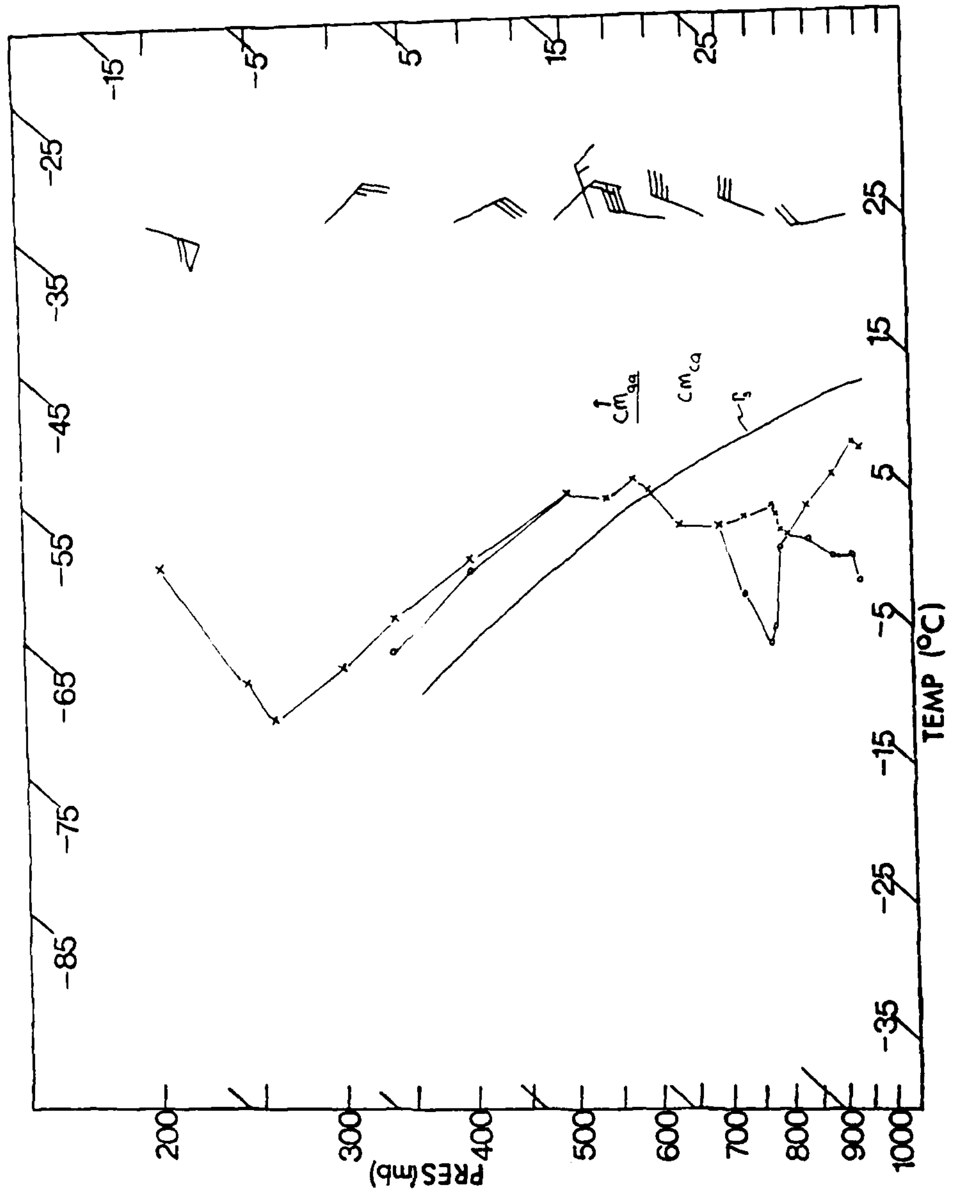


Fig. 12 Sounding for Monett for 14/00 GMT plotted on a skew-t.

14/00 GMT. The frontal inversion at 600 mb and the veering with height of the winds marks the lower boundary of the CM_{aa} flow. This flow extends well west of the surface low and is producing precipitation in Western Arkansas. The CM_{ca} flow which produced the TS in St. Louis is well illustrated at 14/12 GMT on the 286K isentropic surface (Fig. 13). This flow also exhibits strong WAA and vertical motion. Using the advective term of the omega equation on theta-e surfaces gives -10 μb/s at this level. The Peoria sounding (not shown) showed veering with height above a subtle inversion at 420 mb. The significance of this feature will be discussed in section 5.3.

5.2c Southeast Case 24 March 1983

This case clearly demonstrates the open wave occurrence of TS in a developing mid-latitude cyclone. Figure 14 gives the surface data for this case. At 24/12 GMT a weak area of low pressure was forming over the Eastern Gulf of Mexico. Atlanta, 300 km to the north, was reporting thunder with heavy snow. Snowfall totals with this storm are given in Fig. 14b. Ground temperatures and the speed of the system prevented accumulations from being greater.

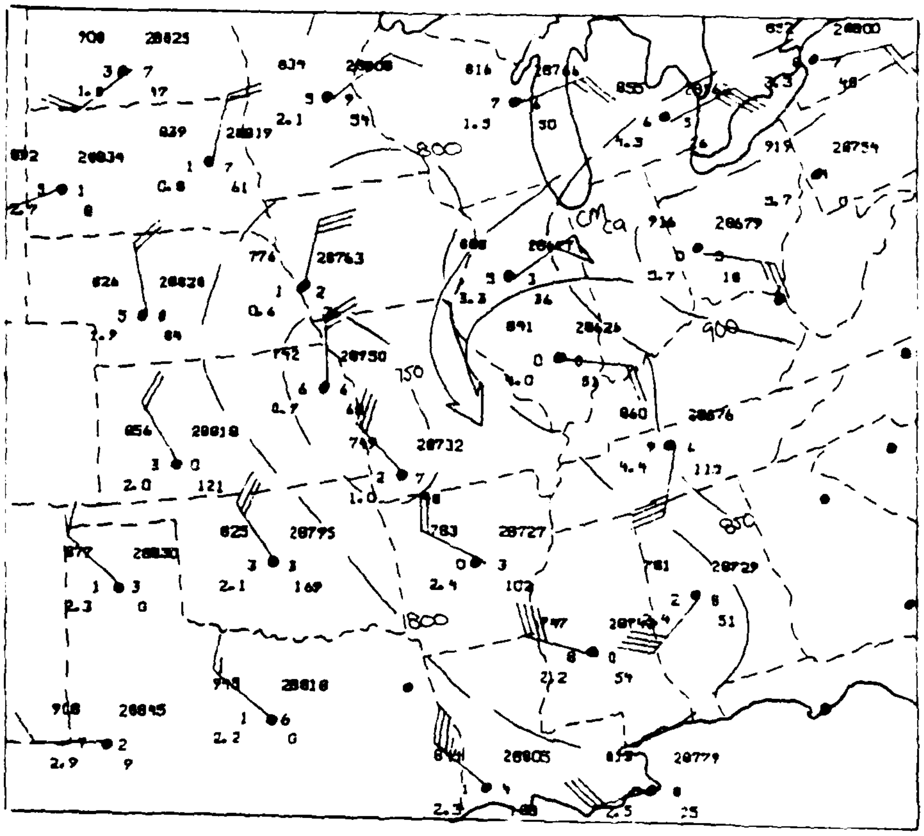


Fig. 13 Same as Fig. 11 except 286K at 14/12 GMT.

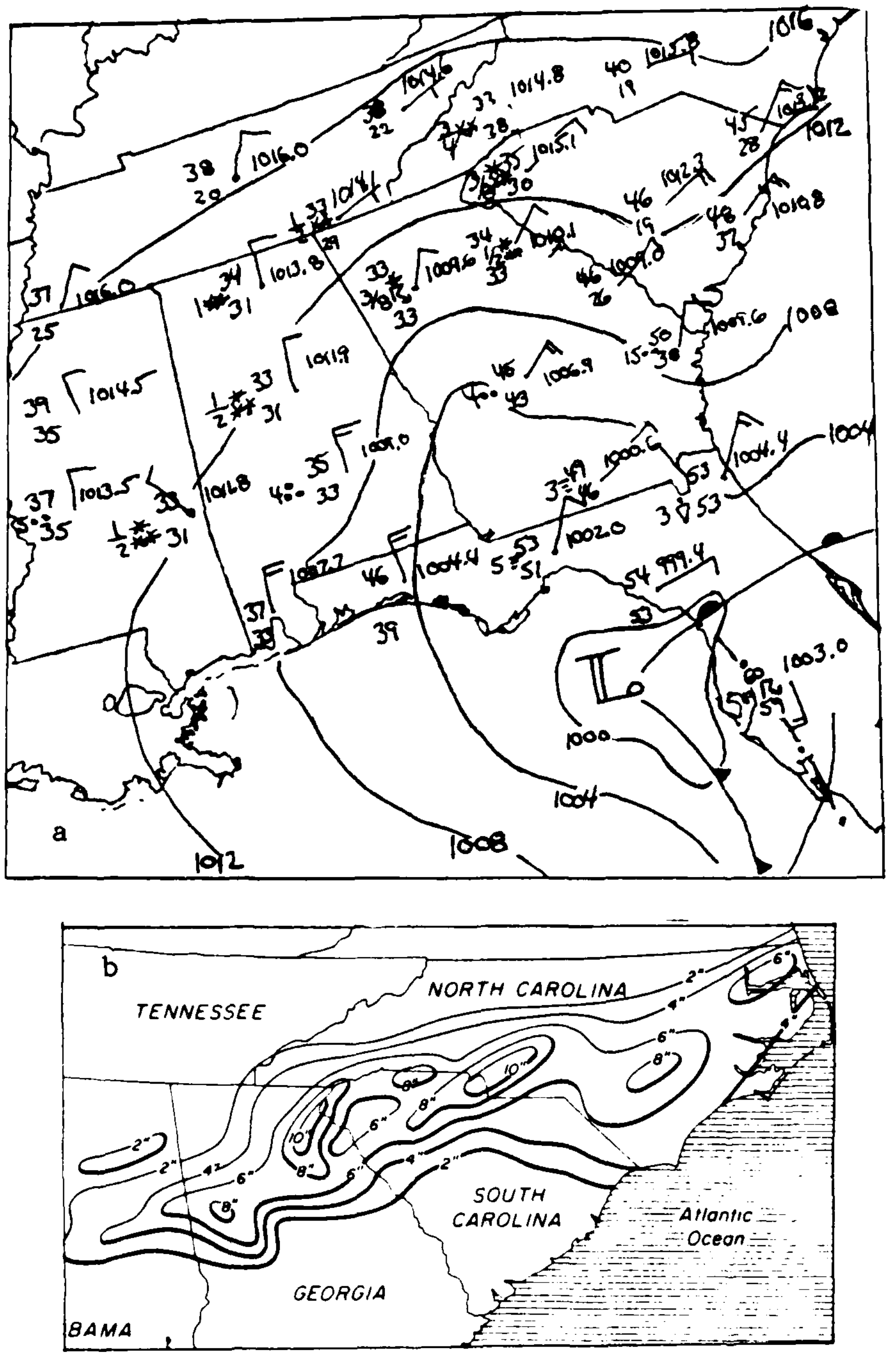


Fig. 14 a) Same as Fig. 9 except 24/12 GMT.
b) Snowfall in inches during 24 Mar. (Storm Data, 1983).

The TS producing CM_{aa} flow is highlighted on the 290K isentropic surface (Fig 15). The flow ascends almost 200 mb from Southern Georgia to Western North Carolina. The effect of saturated ascent can be accounted for by substituting theta-e pressures instead of insentropic pressures. Figure 16 gives the relative-wind isentropic streamline analysis where this is done. The scalloped area defines the saturated environment where theta-e has replaced isentropic pressures. The streamlines can be used as approximate trajectories and show a 300 mb difference across Georgia. With a wind speed of 15 m/s, an estimate of omega from the advective term gives -15 μb/s (50 cm/s).

Figure 17 contains the Athens sounding for 24/12 GMT. In particular note the frontal inversion at 800 mb which divides the CM_{aa} and CM_{ca} flows. The winds veer with height and decrease in speed until 600 mb. At this level the lapse rate begins a slight warming above that of the moist adiabat which is hypothesized as the warming realized from the latent heat of fusion.

5.2d Great Plains Case 25-27 March 1983

On the heels of the Southeast storm,this case reveals Eastern Nebraska recieving heavy snow from

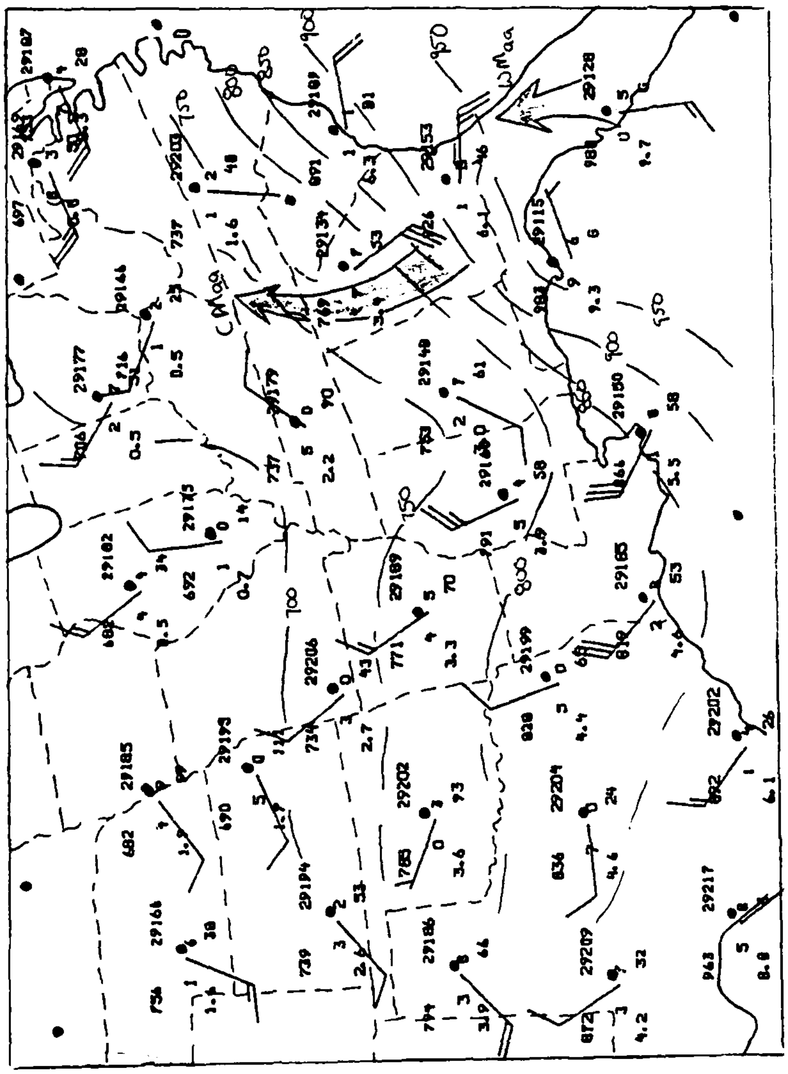


Fig. 15 Same as Fig 11 except 290K at 24/12 GMT.

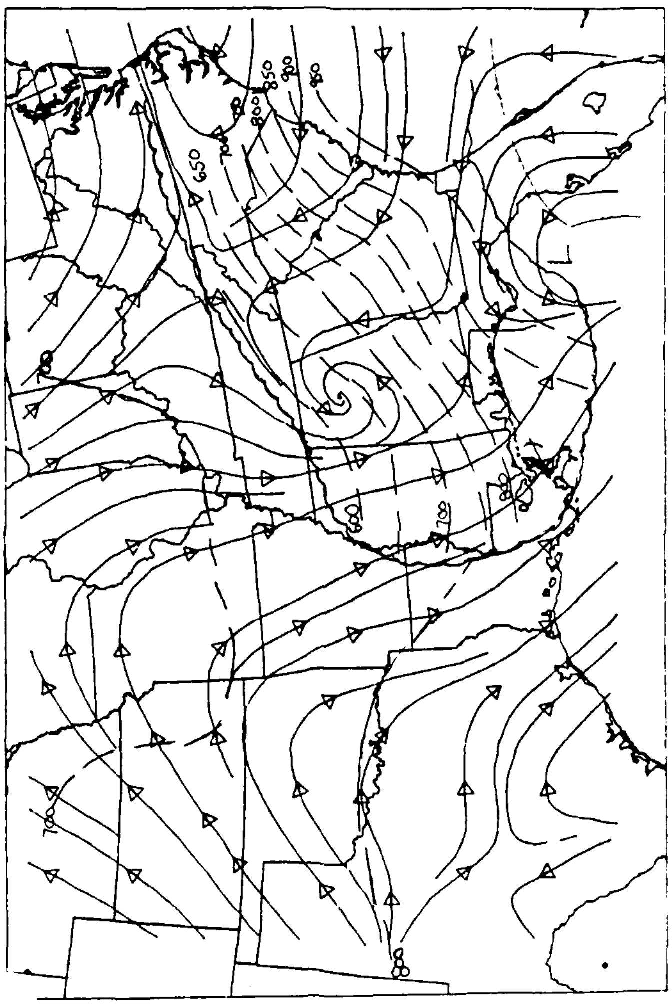


Fig. 16 Relative-wind isentropic streamline analysis for 290K at 24/12 GMT. Scalloped area is saturated where theta-e =302 pressures have been substituted. Isobars are dashed lines at intervals of 50 mb.

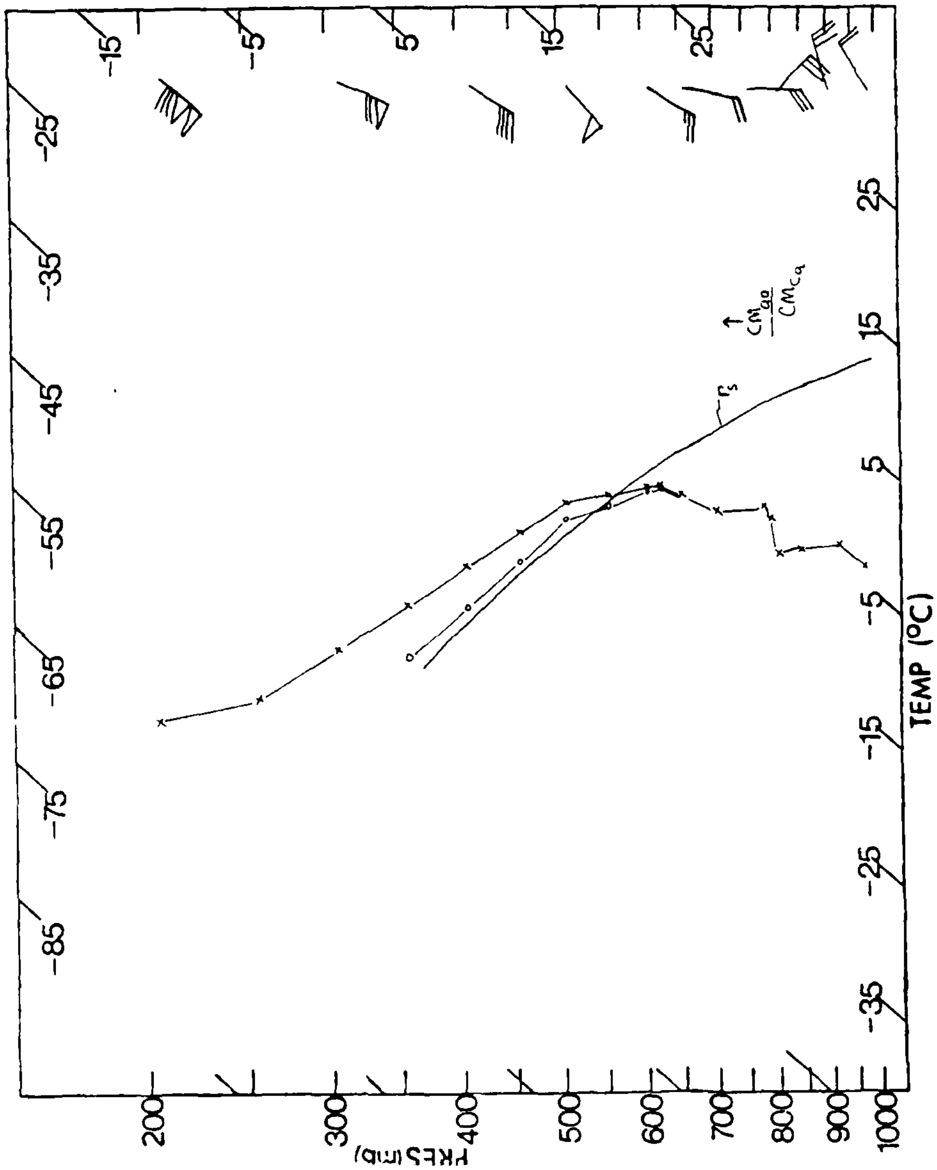


Fig. 17 Sounding for Athens at 24/12 GMT plotted on a skew-t.

both the open and mature phases of the storm. Storm Data (March, 1983) refers to the occurrence of TS, but no surface station ever carried thunder in the weather code. Daylight may have hampered this observation,but this case is still representative of TS in the mature phase. Figure 18a gives the snow totals with this storm. Figure 18b contains the surface map for 26/21 GMT and is a good example of the features expected from Fig. 7c. Thunderstorms have developed along the occluded front from Arkansas to Kansas. Moderate to heavy snow is occurring 200-400 km north of the lowest pressure. Note the easterly flow feeding this region. Omaha's sounding (not shown) contained almost exclusively easterly flow aloft. The main axis of the CM_{ca} flow can be seen on the 282K isentropic surface (Fig. 19). Although the relative-wind isentropic streamline wasn't done on this level, the trajectory is easy to see. Omega is estimated at -10 μb/s as done previously. The confluence of the CM_{ca} and CD_h flows can be seen on North Platte's sounding (Fig. 20). The change in the winds with height is minor,but the inversion at 750 mb makes an adequate distinction between the two flows.

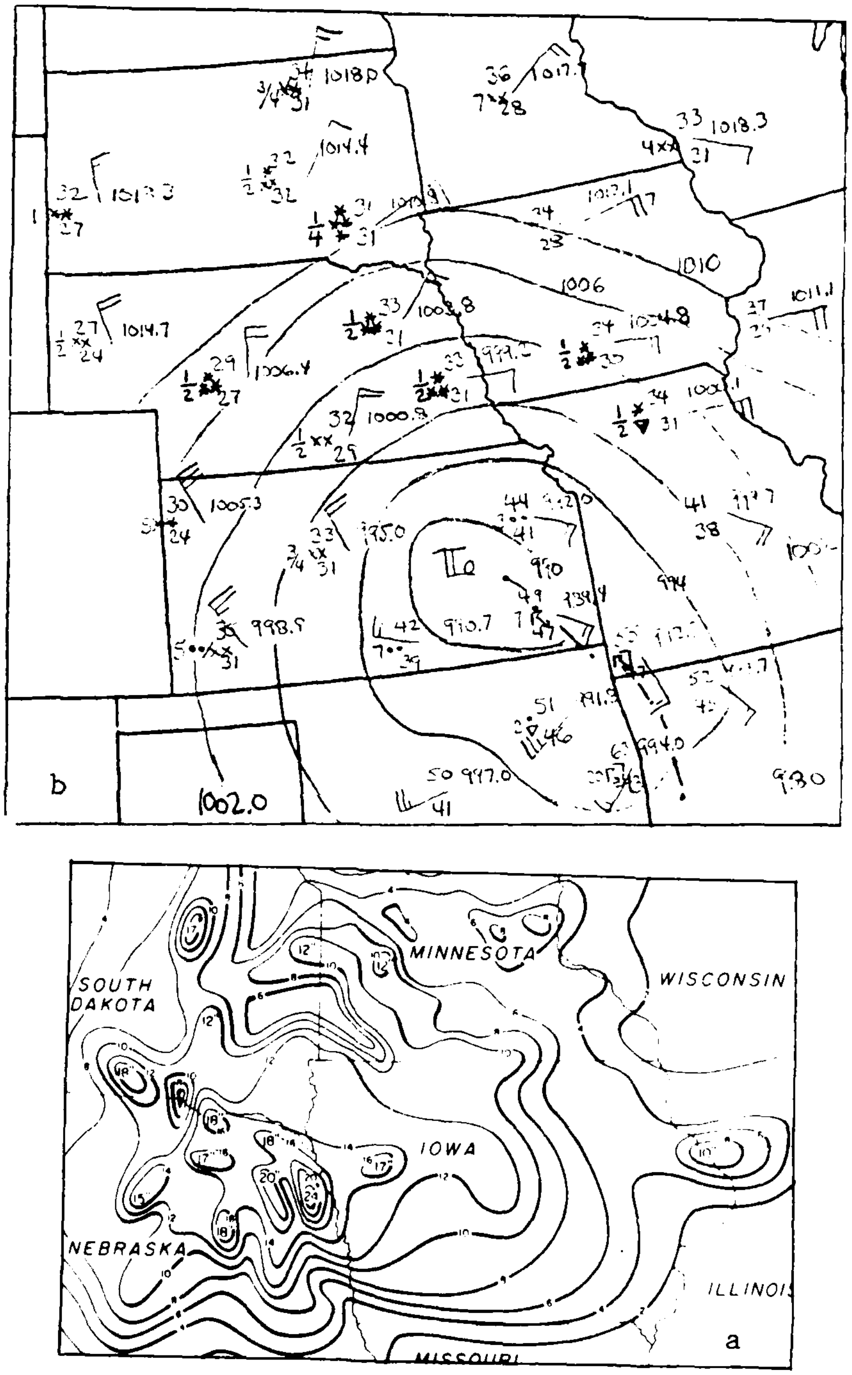


Fig. 18 a) Same as Fig.14b except for 25-27 Mar.
b) Same as Fig. 9 except at 26/21 GMT.

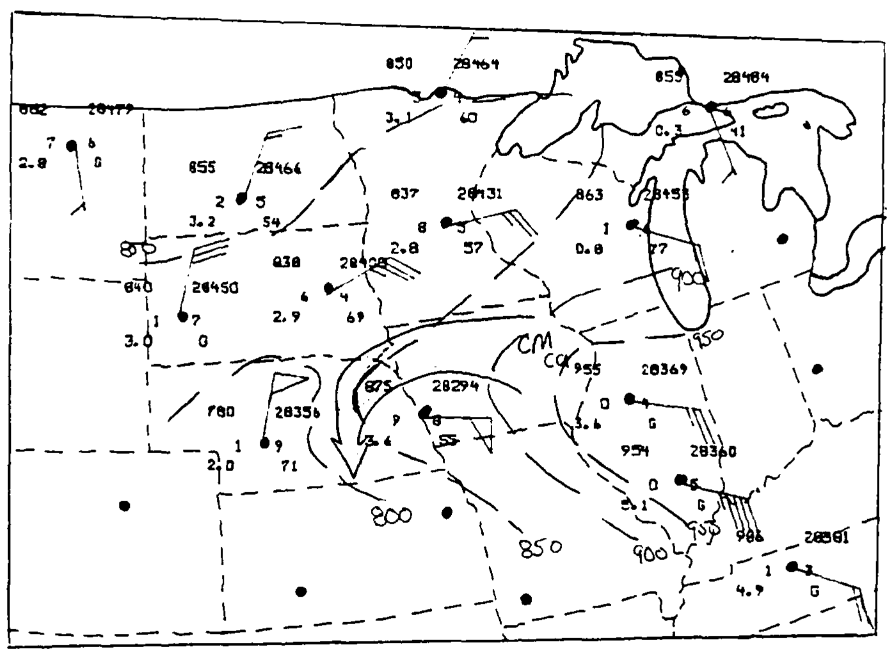


Fig. 19 Same as Fig. 11 except 282K at 27/00 GMT.

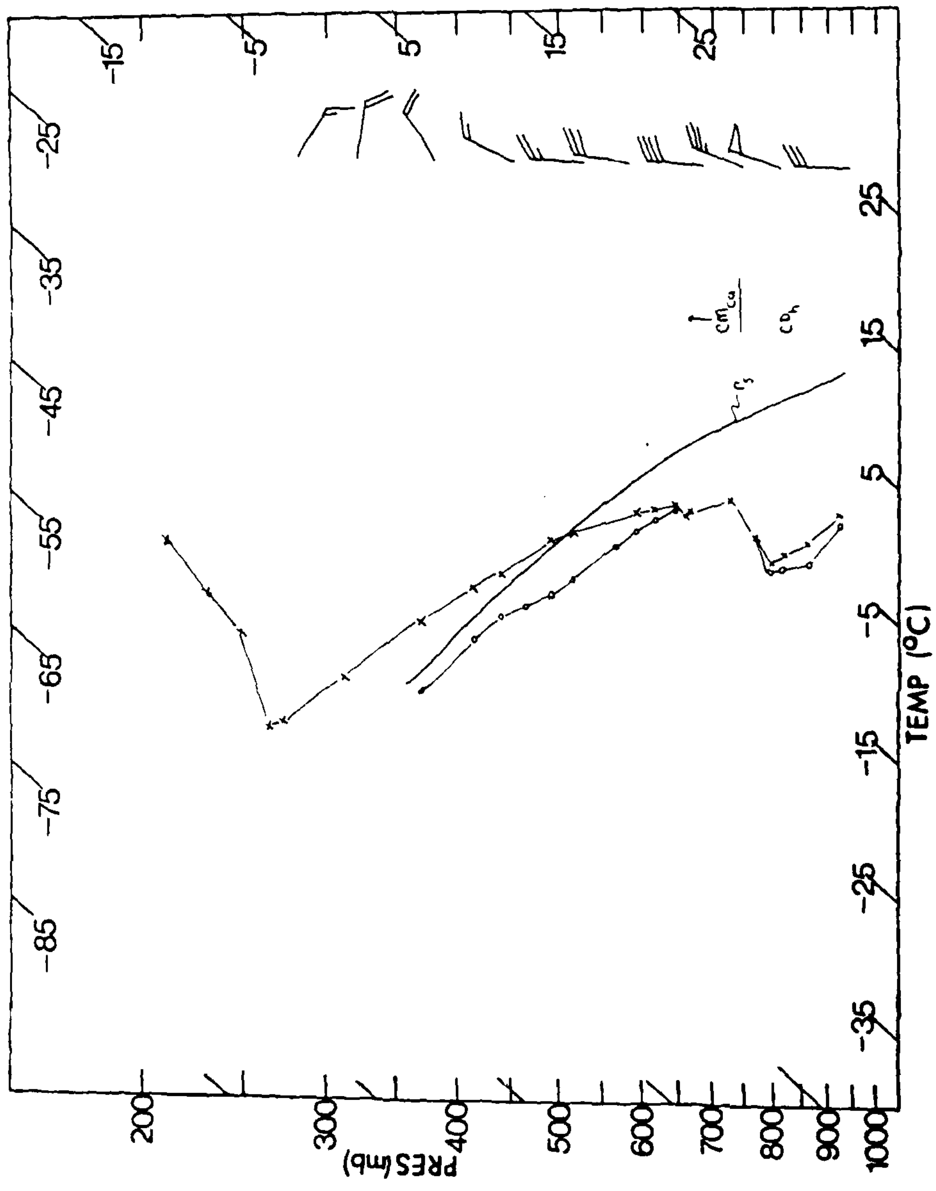


Fig. 20 Sounding for North Platte at 27/00 GMT plotted on a skew-t.

5.3 Discussion

The previous section briefly highlighted some of the observational evidence used to verify the ideas presented by airflow analysis. Cyclone development from an airflow perspective will require much more attention than can be devoted here. The focus of this study is on TS,and the objective of this section is relate these occurrences to the characteristics of the cyclone's airflows.

In the open wave phase Carlson (1980) documented the anticyclonic tendency of air motion in the cold sector. This flow was labeled in this study according to its character as CM_{aa}. Figure 15 reveals the same structure for open wave TS cases. The average distance from the surface low was 300 km indicting a possible critical depth for the CM_{aa} flow before TS can develop. Significant vertical motions were estimated in the saturated environment,but conventional stability indices showed a very stable structure. The Showalter and Lifted Indices had values greater than +15; the K Index averaged less than 10, and Total Totals averaged less than 30.

The CM_{ca} flow in the mature phase was seen to be similar to Browning and Hill's (1985) polar trough.

Figures 13 and 19 show a consistent structure of this airflow. TS reports occur about 250 km from the low in this phase also indicating a possible critical depth needed for development. Vertical motions and stability values are similar to the open wave phase.

Theta-e cross sections were created for all cases and revealed a consistent trend for both phases. Figure 21 is the composite of these. The ascending airflow had a sustained vertical motion of about -5 μb/s at the middle levels (500-700 mb). At lower levels the slope of the theta-e surfaces is much greater due to the larger amounts of moisture and latent heat release. A maximum of vertical motion is realized in this region with estimated values of -15 μb/s (50 cm/s).

Another source of data was provided by the MIT Doppler radar (Bosart and Sanders, 1985; Sanders, 1986). Vertical wind profiles were used to compute vertical motions (Fig. 22). The winds are seen to back with time indicating the progression from the CM_{aa} to the CM_{ca} flow. Two maxima of vertical motion are shown associated with the two airflows. Both are elevated off the ground,but the CM_{aa} maximum is higher which might correlate to the open wave TS having a greater average distance from the low.

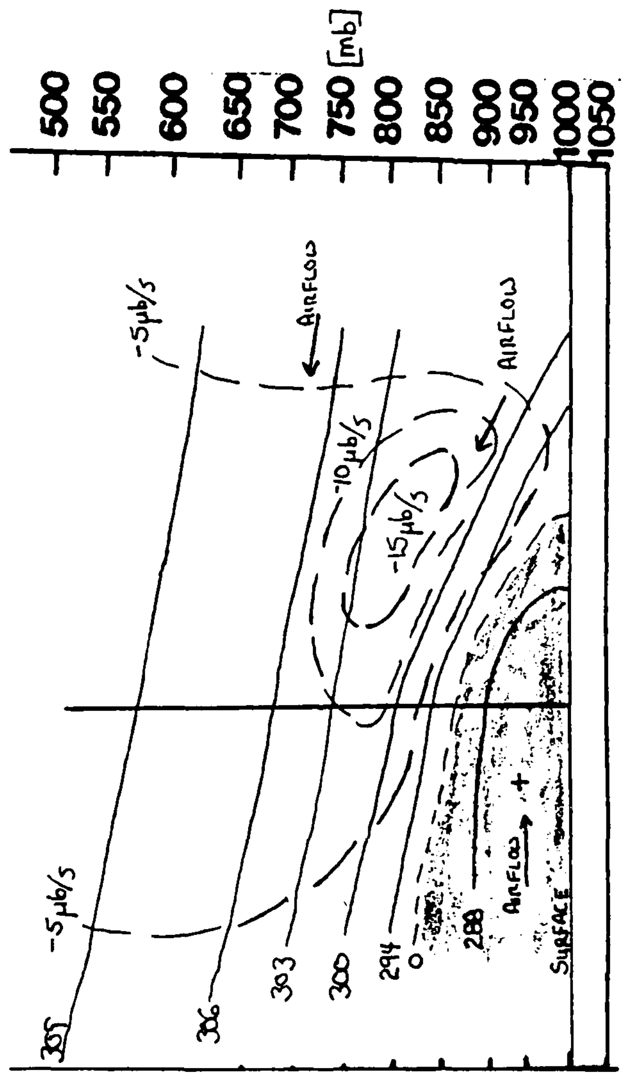
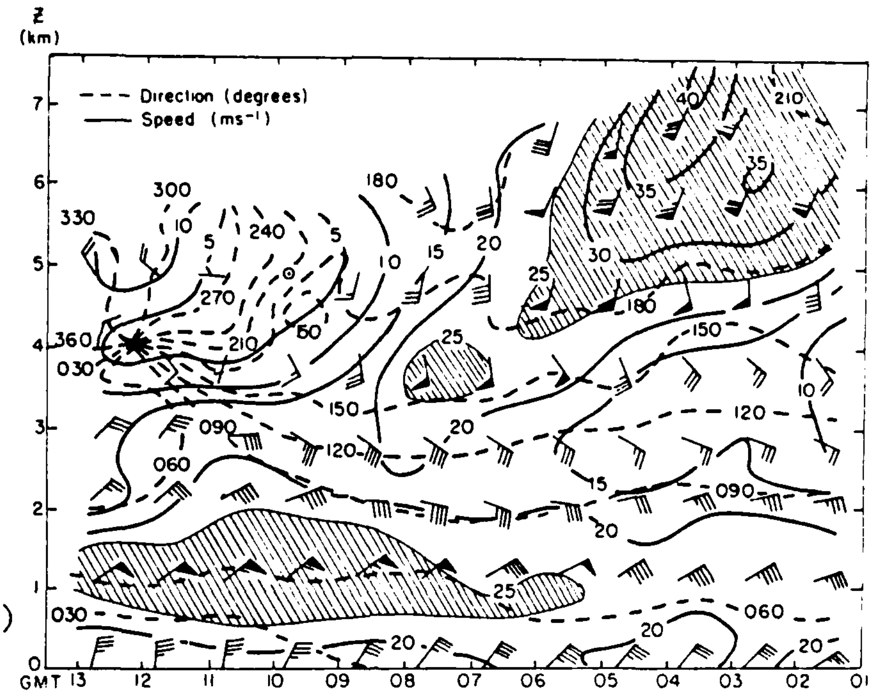
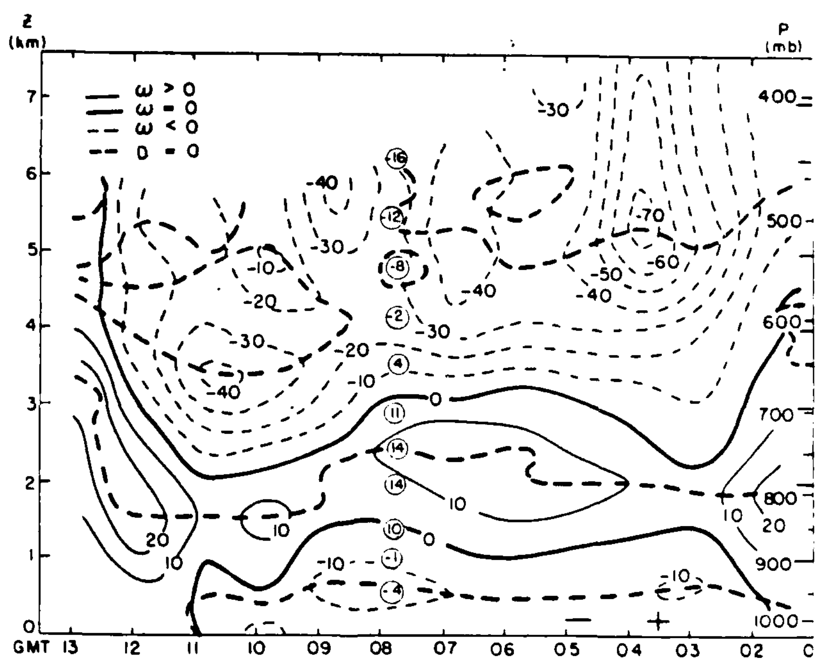


Fig. 21 Theta-e cross section (Composite). Solid lines are theta-e, dashed are omega at intervals of -5 µb/s. The shaded region contains positive omega (downward motion).



a)



b)

Fig. 22 a) Doppler wind profile
b) Omega computed from a) (Bosart and Sanders, 1985).

The cold sector flow's vertical motions are more impressive than the 10-20 cm/s applied to the warm frontal regions. This questions the previously established ideas on precipitation and moisture distribution by Danielsen and Bleck (1967),Carlson (1980), and Browning (1986). They emphasize the moisture in the cold airflows first must fall from the warm frontal clouds. This may not be completely accurate and illustrates a warm sector bias in that certainly all precipitation must come from warm, moist air. Precipitation production deals with relative humidities,and warm sector air is not required. As an example, consider a layer of air at 950 mb which has a temperature of 10°C and a dewpoint of -5°C. When it is lifted with a vertical motion of -10 μb/s, it will saturate within 200 mb and in less than 6 hours. This is only a small part of the life cycle of a mid-latitude cyclone. What seems like dry air is quite capable of producing cloud elements and precipitation. Many systems never produce productive warm sector airflows, and the precipitation is produced solely from the cold sector. The most efficient redistribution of moisture may occur between the CM_{aa} and CM_{ca} flows. That is, the maximum precipitation from the open wave phase saturates the air feeding the CM_{ca} flow.

Soundings present a source of data that suffers from misinterpretation. Our analysis of upper level frontal inversions is limited to the description from the traditional frontal theory. Figures 12,17,and 20 contain soundings that show frontal inversions which are produced by cold sector airflows. Undoubtedly, these would be analyzed as warm frontal by contemporary standards since there is veering with height. Veering with height implies WAA but doesn't describe the source of the airflow. The soundings north of mature cyclones indicated a consistent shift from the CM_{ca} to the CM_{aa} between 600 and 400 mb. Cloud pro- ion,if any, would cirrus in a temperature range of -25° to -60°C (approximately). This has some important impact on the use of satellite data.

Steigerwaldt (1986) states the heaviest precipitation occurs within 1-2° on the southern side of the tight IR gradient. This close correlation may tell little about the mechanisms producing that precipitation. The MB and CC enhancement curves commonly used in operational imagery highlights the high level clouds from -20 to -70°C. The clouds associated with TS are much warmer than this. Figure 23 is a CC enhanced IR image for 1231 GMT on 19 January 1987. TS was reported around St. Louis at this time. The tops

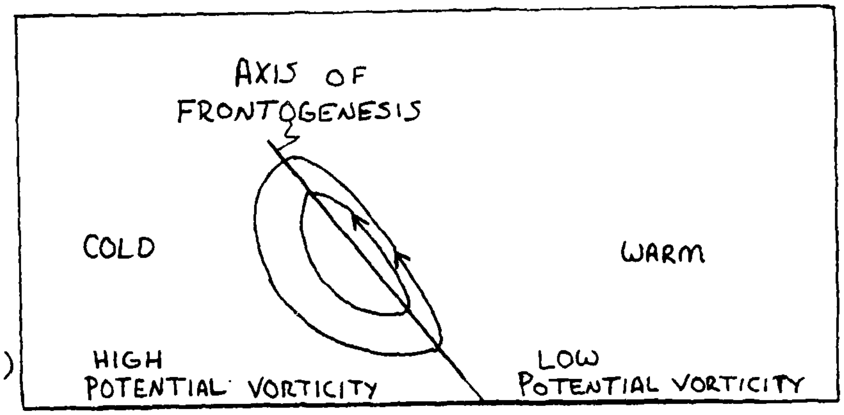
Fig. 23 CC enhanced IR image for 19 Jan. 1987. The band of clouds oriented SW-NE over East Central Missouri was producing TS. TS tops are about -20°C.

of these clouds are about -20°C and are associated with the CM_{ca} flow. The colder cirrus over Illinois and Indiana are associated with the CM_{aa} flow as is the case with mature cyclones. This comma head (Weldon, 1979) is not directly contributing to the development of the St. Louis TS. The favorable temperature range to analyze TS signatures would be -10 to -20°C. Also seen in this image is a stair-stepped IR gradient in the clouds over the Applachian Mountains. This would compare to the visual imagery observation made by Carlson (1980) about the confluence of the warm and cold sector airflows. Beckman (1986) and Bosart and Sanders (1985) pointed to cold cloud tops as indicators of TS; imagery used in this study indicates that warmer tops are associated with TS. Satellite data will be used in the future to track such things as TS,and it is important that this data is interpreted properly.

Recent articles (Bosart and Sanders, 1985; Emanuel, 1985; Sanders, 1986) have emphasized frontogenetical forcing and CSI. Since TS cases were used in their investigations, it is appropriate to comment on their approach. Emanuel starts with the Sawyer-Elliasen equations and applies a two dimensional geostrophic case with a new twist. He introduces a change of

potential vorticity across the front (Fig. 24) and produces an enhanced vertical circulation on the warm side. Latent heat release provides the mechanism for destroying the potential vorticity. This product does not agree with an empirical treatment of frontal zones (Fig. 24b). Simply put three dimensional airflows produce three dimensional fronts. The fronts will have characteristics of the airflows that produced it. Frontal zones have vertical motion but not a transverse circulation as indicated by Emanuel. The air on the warm side of the front is ascending. This ascension is enhanced by latent heat release. The thermal gradient across the front increases the air motion providing more latent heat release to further enhance the upward motion. The cold air side of the front is subject to evaporative cooling which enhances the negative buoyancy and the descent. The viscous shearing between the two flows is what is analyzed as the frontal boundary. From this point of view, the front is created and maintained by the airflows; the phenomenon would be attributable to the flows not the front. It is evident that the geostrophic arguement may have been overextended in an effort to explain TS formation. This is one of the reasons an empirical approach was emphasized for this study,so some truths could be found concerning TS before a theory is applied.

a)



b)

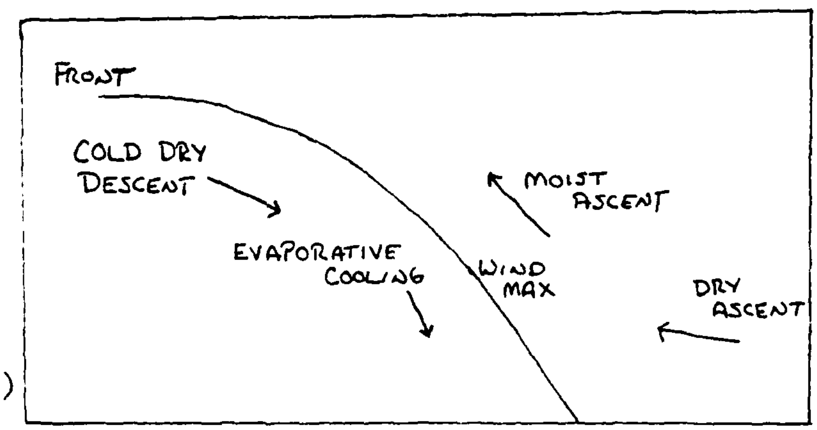


Fig. 24 See text a) (After Emanuel, 1985).

The cyclone development section was intended to do several things. First, a more useful picture of a mid-latitude cyclone was presented through the airflows that produced it. In so doing it was demonstrated the occlusion was formed by cold sector airflows <u>not</u> warm sector ones. Second, the TS occurrences were associated with these airflows and there was some consistency to this relationship. Observational evidence verified these ideas. Finally, other tools such as soundings and satellite reveal additional information about cyclones and TS when interpreted from an airflow point of view; current theoretical treatments provide little insight into TS development.

A lot of information has been provided about the synoptic and mesoscale processes,but TS are still somewhat of a mystery. One area not touched on thus far is the cloud physical microscale precipitation processes which act under the influence of the large scale flow. These will be evaluated in the next section.

6. Cloud Physical Microscale Processes

Obviously researching thunderstorms is not just a question of vertical motion and instability. The electrification process must be considered since it is responsible for producing the lightning. Precipitation production is the key element in generating enough charge to create the lightning necessary in a thunderstorm. TS is no different; it is natural to start with the snow production process. It is the objective of this section to explore these processes and relate them to the synoptic scale to create a comprehensive conceptual model of TS.

6.1 Snow Production

A general background in cloud physics was provided by Byers (1965) and Mason (1971). Jiusto and Weickmann (1973) and Heymsfield (1977) provided most of the specific background used in this part of the study. Snow structure studies were conducted by the author during the winter of 1986-87 to help document the ideas presented in this paper.

Jiusto and Weickmann (1973) formally connect snow structure with the processes that created them. It was apparent that a great deal could be derived from this type of research and prompted the study

conducted by the author. In order to simplify this treatment only the main points concerning snow production will be covered. These mechanisms include diffusional growth,aggregation,and accretion.

Ice crystal growth by diffusion produces characteristic signatures depending on the temperature and water vapor available. Figure 25 shows the categorized shapes with respect to temperature and humidity. These perfect crystals are often the ones displayed in photographs and are the popular forms when snowflakes are drawn. However, in nature single crystals are usually found only on the edges of precipitation bands or in light intensity snowfall.

Typical snowflakes are aggregates of many ice crystals. Aggregation is the process by which ice crystals "stick" to one another; numbers vary from a few per flake to hundreds. Dendrites and needles are favored for forming aggregates though other forms aren't excluded. Dendrites offer "hooks" to capture other crystals. In addition, as crystals fall into warmer temperatures (>-10°C) a thin coating of liquid water is likely to form adding to their adhesiveness. Needles are the favored crystal produced in these warmer temperatures and often accompany snowflakes.

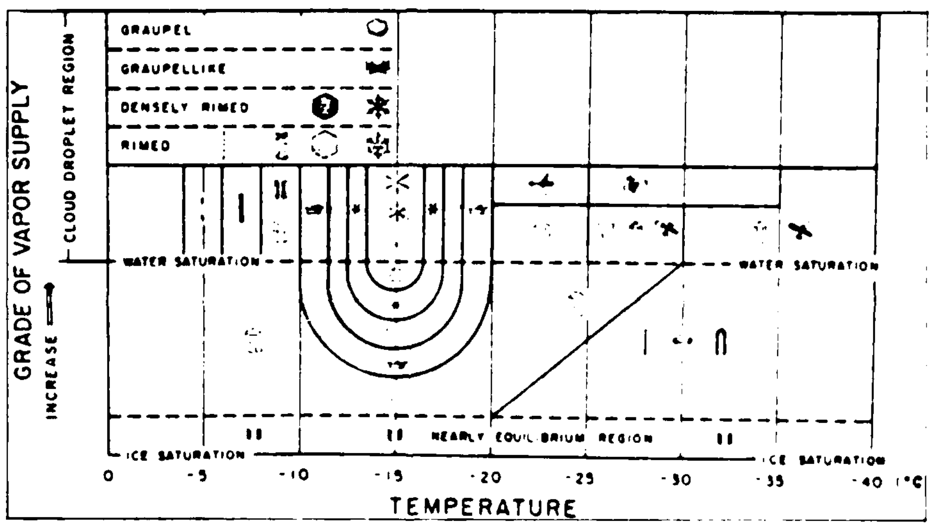


Fig. 25 Ice crystal habits with respect to temperature and water vapor (From Jiusto and Weickmann, 1973).

The atmosphere is limited in its ability to convert water vapor into the ice phase. Diffusional growth is slow and activation of ice nuclei is dependent on colder temperatures. In sub-freezing supersaturated environments, condensation nuclei offer an alternative to the vapor phase. Supercooled droplets are common in the atmosphere with a range of 0 to -20°C though they have been documented at -40°C (Mason, 1971). Supercooled droplet populations are also dependent on moisture content and vertical motion (Heymsfield, 1977). Heymsfield further defines this region between 0 and -10°C with vertical motions around 50 cm/s.

Accretion (*riming*) is the capture of supercooled droplets by ice crystals or other solid hydrometeors. Aggregates offer a large surface area to capture these droplets. Lew, et al. (1986) document that the porosity of the crystal/flake increases the collection of droplets by an order of magnitude. Byers (1965) states 75% of precipitation is acquired in the lowest levels of the atmosphere. Accretion plays a key role in this process.

Collisions with supercooled droplets or other crystals causes splintering of fragile dendrites. These fragments then offer a new base for diffusional

growth to continue. Supercooled droplets are also believed to splinter upon freezing (Mossop, 1976). These fragments contribute to the chaotic appearance of large snowflakes.

The three growth processes: diffusion,aggregation,and accretion will operate simultaneously at the height of a heavy snowfall. Snow will then take one of the following forms: rimed or unrimed crystals, rimed or unrimed aggregates,or graupel. Graupel usually takes the form of symmetric cones;however, there can be some confusion distinguishing between a heavily rimed aggregate and graupel. A logical progression in an idealized snowstorm would be single crystals to unrimed aggregates to rimed aggregates to finally graupel in the heaviest snowfall. Jiusto and Weickmann (1973) state large graupel formation is associated with lightning in lake effect snow squalls. Graupel formation does not necessarily produce enough charge to produce lightning. An arctic frontal passage was analyzed for snow structure; during the heaviest precipitation 5 mm graupel was observed but lightning and thunder were not. Documenting the snow structure within a TS was the goal when the snow study was started. The best opportunity presented itself on 19 January 1987 over the northern parts of St. Louis and adjacent Southern Illinois. At 19/12

GMT thunder had been reported by several sources according to the NOAA weather radio. St. Louis radar at that time showed a band of snow about 40 km across with no apparent movement. The band had a cellular appearance similar to Bosart and Sanders (1985). Since radar returns are weak and variable in snow, this may be due to several factors. One suggests the presence of supercooled water droplets in greater sizes and concentrations in localized areas. The liquid water droplets even with their smaller size would reflect a greater intensity of the radar beam. The main echo was associated with CM_{ca} flow and appeared stationary with a slight cyclonic rotation with time. By 19/15 GMT the leading edge of the snow could be observed (the observation site was 30 km from the radar); the cellular structure had dissipated. Regretably, no attempt was made to travel to the area where TS was being reported. The author opted to view the radar and hope the TS would continue until the band passed over the observation site.

A dark nylon cloth was used to collect the snowflakes. Table 3 summarizes the findings.

Table 3

Time(GMT)	Crystal Type	Character	Size(Avg)
1500	plates	unrimed	1 mm
1515	dendrites	unrimed	2 mm
1518	aggregates	unrimed	5 mm
1528	aggregates	slt rime	1 cm

The heaviest snow was overhead from 1530-1600 GMT with surface visibility about 600 meters. The aggregates were composed of dendrites,needles,and fragments. Also during this time a few very large (7 mm) stellar dendrites were observed unrimed and as singular crystals.

Documenting the type and character of snow is a powerful source of information. This is especially true for TS cases where the degree of riming could be evaluated and used as an indicator for the electrification processes contained within the storm.

6.2 Cloud Electrification

Cloud electrification studies have focused primarily on air mass and warm sector type thunderstorms. Electrification in snow isn't as well documented. Takahashi (1983) describes the electrical structure noted in snow showers. Takeuti and Nakano (1978) and Brook,*et al*. (1982) have also studied winter convection. Regardless of the season, two mechanisms are

viewed as contributors to thunderstorm production: induction (polarization) within an electric field and thermoelectric effects of ice and supercooled water (Kuettner, et al., 1981). The contribution of both is fiercely debated. Depending on the conditions induction can be shown to dominate (Ziv and Levin, 1974), or the thermoelectric effects can dominate (Takahashi, 1978).

The most obvious similarity between snowstorms and rain producing warm convection is riming. Both contain this process only to varying intensities. The induction process is related to updraught velocity, particle fall speed,and strength of the electric field present all of which would be more significant in warm convection. Takahashi (1978) emphasizes the riming in winter convection and gives a means by which to quantify this process.

Takahashi researched the changes in charging associated with riming when the temperature and cloud water content are allowed to change. Figure 26 is taken from Takahashi (1978) and summarizes his findings. He presents a series of equations to check the time required to achieve breakdown potential (3000 V/cm). The major term takes the form of:

$$F=-2t^2\pi^2NV^2R^2nqE$$

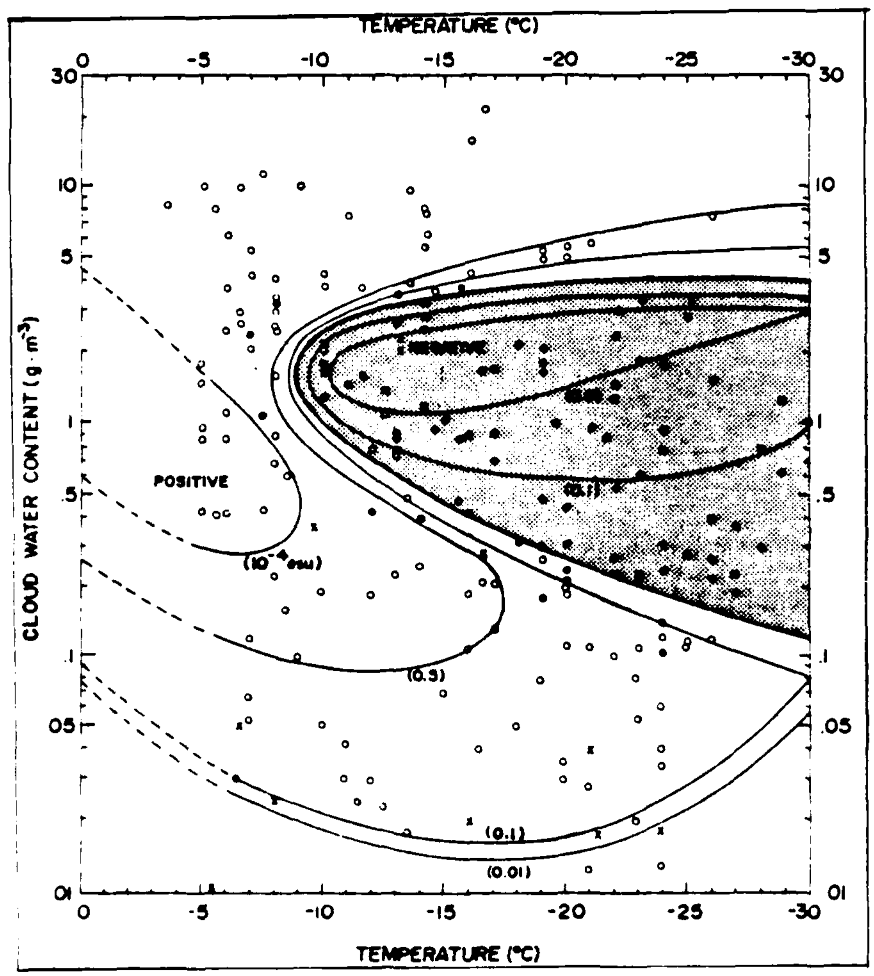


Fig. 26 Riming charge and polarity with respect to temperature and cloud water content. Open circles indicate positive rime, solid are negative (Takahashi, 1978).

where F is the electric field, N the number of graupel particles, V the fall velocity of the precipitating particle, R the size of that particle, n the number of ice crystals, q the electric charge separated per collision,and E the collision efficiency. By assigning representative values, Takahashi shows that lightning can be produced within 5 minutes. This is within the acceptable time constraint posited by Mason (1971) of 30 minutes (lifetime of a cumulonimbus).

In order to use this equation to show electrification in snowstorms it would be necessary to find some representative values of our own. We found earlier that the vertical motion was around 50 cm/s. This was computed from synoptic data and represents the base vertical flow. Local generating cells will have a much greater vertical velocity (Heymsfield, 1977). We will use the conservative figure. Again from Heymsfield, with 50 cm/s at -10°C ice crystal concentrations are roughly 100 per liter. With aggregation 50 per liter would be representative at -5°C which is similar to the values established by Jiusto and Weickmann (1973). The emphasis is placed on rimed aggregates so only one graupel patricle per m^3 is used. A 5 mm aggregate will have a fall velocity of 200 cm/s. The amount of charge separated per collision is 10^{-4} esu at a water content of 1 g/m^3. The colli-

sion efficiency (Lew, *et al.*, 1986) is chosen as .5. So we have F=3000 V/cm, N=1 m^{-3}, V=200 cm/s, R=5 mm, n=50 l^{-1}, q=10^{-4}esu, and E=.5. When solving for t this gives 24 minutes to reach breakdown potential. This is still within in the guidelines established by Mason (1971) even though this isn't the classic cumulonimbus. Personal observation of TS puts the frequency between 10-15 minutes so the calculated values are realistic. This also indicates graupel formation isn't required though certainly riming is paramount. Of course the values taken here are somewhat conservative,but the point is lightning can be generated in an environment less impressive than the typical warm sector thunderstorm.

In the typical thunderstorm the main charge is negative and exists between -5°C and -25°C. During cloud to ground strokes, lightning brings down negative charge (Kuettner, *et al.*, 1981). In winter convection (Takahashi, 1983; Brook, *et al.*, 1982) the main center of charge is positive and lower in elevation. The positive charge brought down with this lightning has been documented, in addition to the above, by Bosart and Sanders (1986). Though there seems to be some question in the minds of the referenced authors concerning the difference in charge, the answer appears to be found in Fig. 26. The main charge would

depend on the updraft and the conditions it establishes for riming. In more developed convection with stronger vertical velocities, the greatest population of supercooled droplets would be higher in the cloud. From Fig. 26 the riming would be negative giving the main negative center of charge commonly observed in thunderstorms. In shallow convection the riming would be at warmer temperatures and therefore positive. Granted, this is a simplified approach, but these generalizations help in deducing the electrical structure of TS.

6.3 Conceptual Model of TS Development and Structure

It is now possible to pull a few of the ideas from this study together to construct a conceptual model of a thunderstorm with snow. Figures 27 and 28 illustrate these ideas. In Fig. 27 the cloud depth of the ascending, cold, moist, flow (CM_{aa} or CM_{ca}) is extended by local convective elements. This would enhance ice crystal production around -15°C which is favored for maximum production (dendrites/plates). As the dendrites grow and become fragile, they will splinter. The fragments will carry away a positive charge (Mason, 1971) and stagnate until their fall velocity becomes greater than the vertical motion. The larger crystals will fall to warmer temperatures

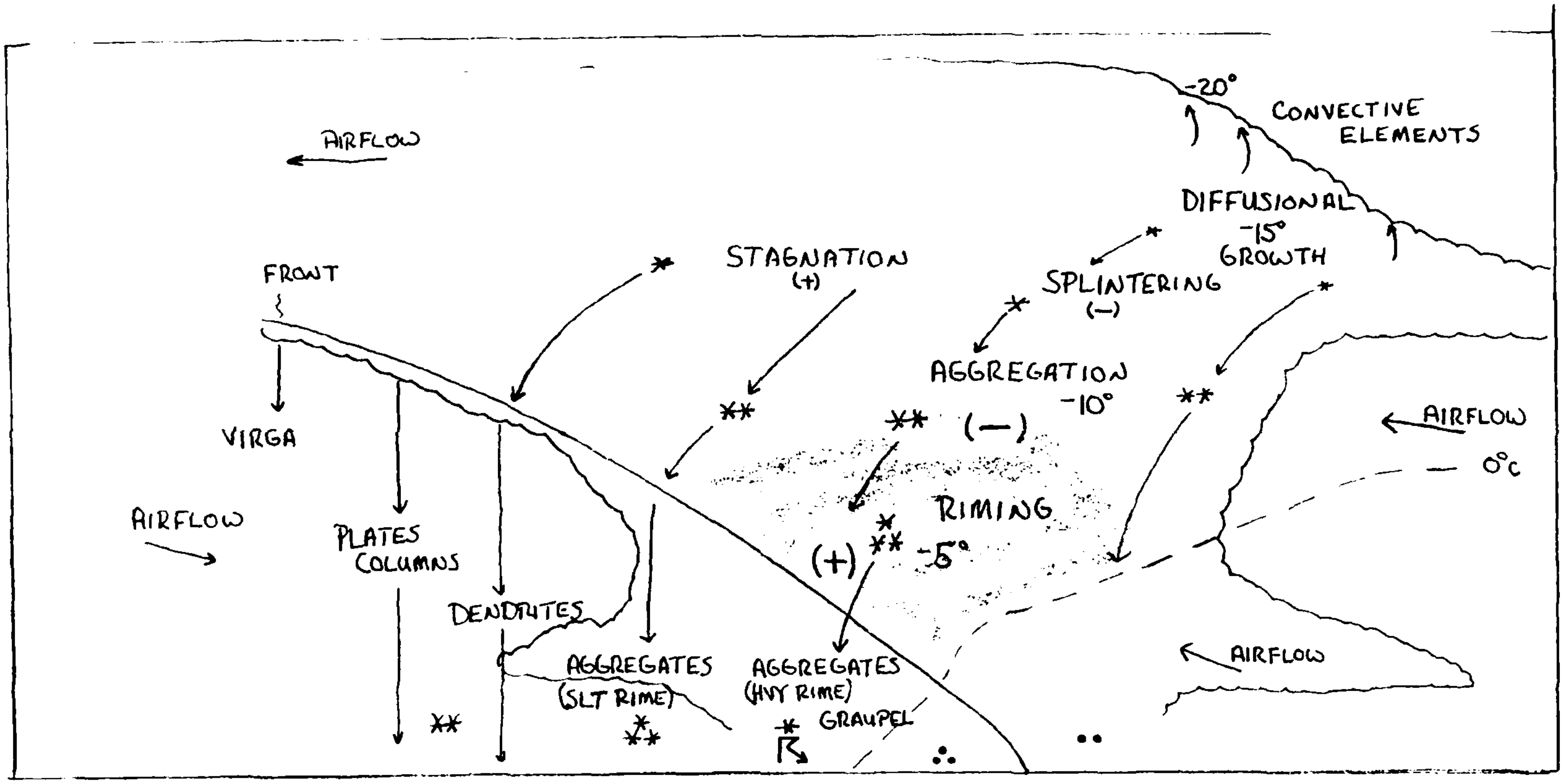


Fig. 27 Conceptual model of a thunderstorm with snow (see text).

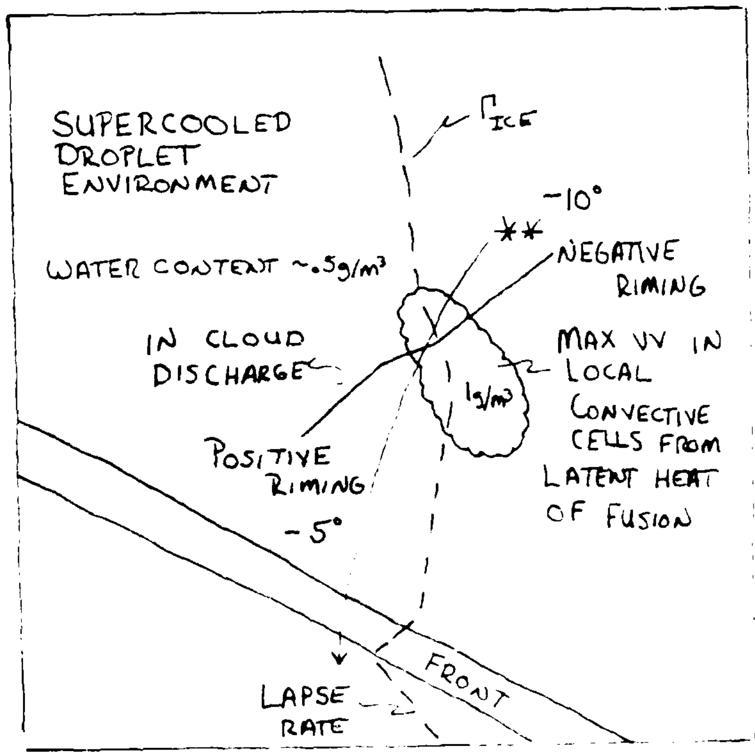


Fig. 28 Enlarged view of the supercooled droplet region (shaded area) from Fig. 27 (see text).

while being carried downwind. Aggregation begins around -10°C producing larger snowflakes;these aggregates will possess a negative charge. Riming at this level will be negative further enhancing the negative charge of the snowflakes.

It is significant to note that the maximum vertical velocities were found at levels from 0° to -10°C (Fig. 21). The atmosphere's inability to convert water vapor into the ice phase means greater populations of supercooled droplets are produced in this region. Riming at this level will be positve. The glaciation of this supercooled water releases the latent heat of fusion which provides as much as 1°C of warming over several hundred meters (Saunders, 1957). These positively buoyant pockets would further enhance the presence of supercooled water (Fig. 28). They would account for the cellular structure on the radar. Substantial charges would be generated in localized areas giving rise to in-cloud discharges. Personal observations confirm this though a cloud to ground stroke would be hard to observe in moderate or heavy snow.

TS would have a horizontal extent of 10 to 100 km depending on the conditions for riming. The total vertical cloud mass would be around 3 km though the most significant charging would occur in 10% of that

cloud depth.

Fall velocities of the precipitating particles would increase as they passed from the upward velocity side of the front to the neutral or downward velocity side. Significant modification of this air can take place due to the melting of the snow if temperatures are that warm (Wexler and Reed, 1954). The progression of precipitation type with relation to the airflow is given along the bottom of the figure.

Given the observational evidence available this is a comprehensive,conceptual model of a thunderstorm with snow. It is different from what the conventional thunderstorm is understood to look like. Granted there are occurrences of TS that resemble there warmer cousins in structure,but the majority of TS will resemble this cold air type.

7. Conclusions and Recommendations

There were three objectives at the beginning of this study. First, the occurrences of thunderstorms within areas of snow needed to be documented. These were shown to exist in relation to the mid-latitude cyclone. Two major areas were noted in conjunction with the developing and mature phases of these cyclones. The second objective was to present a clearer conceptual model of cyclones, how they evolve, and how TS are related to this development. The cyclone was analyzed by characteristic airflows which revealed a major role played by the cold sector. The cold sector appears to be the key element in maturing the cyclone and producing the occlusion. The cyclonic and anticyclonic components of the cold sector flows were shown to ascend and develop the environment needed to produce heavy snow. Finally, the cloud physical microscale processes were linked to the synoptic scale to create a comprehensive, conceptual model of TS structure. Snow production contains the necessary ingredient of riming which allows under certain conditions to produce lightning. The riming was quantified to show breakdown potential being reached within [illegible] minutes for a snowstorm. The conceptual model of a typical TS was given, and the processes illustrated.

Predictability of TS wasn't touched upon in this study. Conventional tools are not sufficient to pinpoint the likelihood of development. Continued tracking of TS may fine tune the synoptic tendencies outlined in section 4. Nevertheless, this study has pointed the way for various avenues of investigation to continue. Directly related to TS research is the need to record and analyze the type and character of snowfall. This evidence will provide tremendous insight into the snow and electrification mechanisms, and how they vary with different types of storms. This is an used resource. Standard observations record the types of clouds which is very useful in analysis and forecasting. The same can be done for recording snowfall type.

Airflow analysis has provided a new way to treat cyclone development. The importance of the cold sector has only begun to be understood. Since East Coast storms weren't included in this study an interesting concept hasn't been discussed. It appears secondary development of low pressure areas along the lee of the Appalachian Mountains is related to the redefining of the cold sector flows. This would be an interesting area to persue in later research. Along the same line, more study needs to be devoted to the maturing process of cyclones. The idea of the

cold sector producing the occlusion is a new one and will require further documentation. Documentation of TS should continue,but thunder with rain on the northwest side of cyclones should be included to see how the signatures vary. With this sort of documentation we will be able to refine the satellite enhancement curves to reveal the actual signatures and not close correlations.

In this study it became increasingly obvious the current state of meteorology is beset with too many biases and theoretical applications. Isobaric charts and application of quasi-geostrophic theory are not adequate to explain TS. There is a need to once again go back to the observational evidence and understand the actual processes that shape phenomena around us. Thunderstorms with snow are such an area,and hopefully new light has been shed not only on this phenomenon but others as well.

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Harold Alan Elkins was born on 20 March 1960 in Chattanooga,Tennessee to Col. and Mrs. James T. Elkins. He attended Chattanooga Central High School and graduated in 1978. He chose to study meteorology at Saint Louis University where he graduated cum laude in 1982.

Harold wanted to apply the education he had received before continuing to the Master's Program. He was commissioned an officer in the United States Air Force after graduation and was stationed at Barksdale AFB, LA. Most of the time was spent dealing with forecasting including 6 months in Europe working with British and German weather agencies. In 1985, the Air Force offered Harold the opportunity to return for his Master's degree.

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